HURDLING THE CHALLENGES OF THE 2019 IAAF WORLD CHAMPIONSHIPS

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HURDLING THE CHALLENGES OF THE 2019 IAAF WORLD CHAMPIONSHIPS

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EDITORIAL
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Editorial: Hurdling the Challenges of the 2019 IAAF World Championships

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Keywords: athletics, heat stress, running mechanics, injury prevention, pacing strategies

Editorial on the Research Topic

Hurdling the Challenges of the 2019 IAAF World Championships

The 17th International Association of Athletics Federations (IAAF) World Championships were staged in Doha, Qatar from September 27 to October 6, 2019. In recent years, the Qatari capital Doha had an extensive history as a host of international athletics events from the first ever IAAF Grand Prix in 1997 to the 2010 IAAF World Indoor Championships and the Doha Diamond League. However, the 2019 IAAF World Championships has been the largest sporting event held in Doha to date in terms of global reach and impact. Doha welcomed over 200 countries and 2,000 athletes with ∼10,000 international guests, 30,000 spectators from outside Qatar, and more than 2,000 media personnel.

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SOLVING REAL WORLD PROBLEMS

This Research Topic includes athlete-centered research advancing the practical knowledge of coaches, exercise physiologists, sport biomechanists, sport analysts, sport physicians, and academic researchers. This unique collection of articles has direct practical applications to address specific challenges associated with 2019 IAAF World Championships and beyond. In particular, the papers address problems encountered by athletes during training or the actual competition, doping issues (Faiss et al.), and the merit of training interventions (i.e., altitude training; Slawinski et al.). The great diversity of athletic disciplines is reflected in this article collection spanning from 100-m sprint to marathon and walking events, and to pole vault. A total of 27 papers have been accepted including 18 original papers, 4 reviews, 4 perspectives, and 1 policy brief article. Those contributions feature over 110 authors arising from over 30 different research groups from more than 20 countries in Europe (e.g., France, Germany, Greece, Hungary, Italy, Netherlands, Spain, Switzerland, United Kingdom), Asia (e.g., Japan, Qatar, South Korea), Oceania (e.g., Australia, New Zealand), Africa (e.g., South Africa), North America (e.g., Canada, United States of America), and South America (e.g., Brazil).

This Research Topic represented a fantastic opportunity for the scientific community to provide up-to-date knowledge and propose solutions to real-world problems for elite competitors. Four key areas have been investigated:

1. Training and competing in hot environments
2. Management of the most common injuries and illnesses
3. Advanced biomechanical analyses
4. Racing and pacing.

TRAINING AND COMPETING IN HOT ENVIRONMENTS

One of the unique characteristics of the 2019 IAAF World Championships was that it was hosted in the Middle-East for the first time. Nowadays, major sport competitions are no longer exclusively hosted in western countries. For example, despite existing since 1896, the summer Olympics were held in South America in 2016 for the first time, while so far have never been organized in Africa. Along the same line, the FIFA World cup exists since 1930 but was hosted for the first time in Asia in 2002, in Africa in 2010 and will come to Middle-East in 2022. This globalization of sport has brought several challenges to the athletes including travel fatigue, jetlag, and environmental conditions.

Hot and humid ambient conditions may play a major role during the endurance events of the 2019 IAAF World championships, the 2020 summer Olympics and many other major sport events. Heat stroke is the second highest cause of death in sport after cardiac conditions but should also be considered for spectators as it accounts for more deaths than all other natural disasters combined in the general population. Moreover, heat stress (due to a combination of heat and humidity) impacts exercise performance. Increasing muscle temperature benefits explosive activities, whereas high whole-body core temperature impairs prolonged exercise capacity in hot and humid environments. This Research Topic includes an original analysis of heat stroke prevalence in runners (Grundstein et al.) and provides applied recommendations for sport and medical communities (Racinais et al.), organizing committees (Bermon and Adami), and ultra-endurance athletes (Bouscaren et al.). It also includes papers addressing issues related to the development of new technologies (Muniz-Pardos et al.).

MANAGEMENT OF THE MOST COMMON INJURIES AND ILLNESSES

Beyond the specific issues of the environmental conditions, this Research Topic also presents applied recommendations to minimize injury and illness during major athletic championships (Edouard et al.). This is supported by original research on injury risk factor in athletics including the effect of team size (Edouard et al.) or a prospective epidemiological study (Carragher et al.). The specificity of the athletic disciplines is highlighted in a review on foot strength (Tourillon et al.) alongside original research on foot orthoses (Van Alsenoy et al.) and lower limb asymmetry (Girard et al.). There is also a specific focus on the 100 m (Fujita et al.) and pole vault (Edouard et al.) disciplines. Those eight articles related to potential injury risk factors represent the largest contingent of this Research Topic. This demonstrates the current interest of the research community in determining the risk factors and developing counter-measures.

ADVANCED BIOMECHANICAL ANALYSIS

The 100-m race is one the most popular athletics event that advanced biomechanical analysis has influenced over the years. Bezodis et al. analyzed the start and initial acceleration technique of the World's best male sprinters and hurdlers *in situ* during the finals of the 2018 IAAF World Indoor Championships and demonstrate many similarities between their kinematics and intersegment coordination profiles. From horizontal force-velocity-power profile data, Stavridis et al. also highlighted that high-level female sprinters are able to apply higher horizontally-oriented forces onto the ground during acceleration phase than the high-level female hurdlers. Using the longest force plate system in the World, Nagahara and Ohshima indicated how the location of the center of pressure on the starting block determines sprint start performance. Leg kinematic features of maximal speed sprinting at different leg length and step characteristics were further elucidated by the same research group using regression equations (Miyashiro et al.). Under treadmill running conditions, Moore et al. evaluated the effect of manipulating ground contact time on the metabolic cost of running in trained endurance runners. Biomechanical analysis not only is critical to improve tolerance to ground impact but also useful to ensure that athletes effectively comply with the rules in Race Walking. For the first time, Hanley et al. proposed an assessment of a large number of qualified IAAF racewalking judges from around the globe to accurately detect legal and non-legal technique, also providing flight times across a range of speeds to establish when athletes are likely to lose visible contact.

RACING AND PACING

Pacing strategies have a considerable influence in determining race outcome by optimizing the limited energetic resources available. It is therefore crucial that young athletes, striving to reach the elite level, adequately develop their pacing behavior (Menting et al.). Middle distance races are amongst the most demanding athletic events, while these races are also characterized by a large variety of runner profiles (Sandford and Stellingwerff). Here, Hanley et al. questioned whether the draws for heats and lanes impact on placings and progression in 800-m championship racing, and proposed that the IAAF could consider allocating the inner lanes to faster athletes rather than the outer lanes. A detailed analysis of tactical behaviors that differentiate medallists in the 1,500-m race is also detailed by Sandford et al.. Knowledge pertaining to the underlying mechanisms and factors influencing the regulation of pace is still not well-understood. Here, Hettinga et al. explored whether World Championship and Olympic pacing profiles differ across middle-distance, long-distance and racewalk events for men and women, and also include for the first time data from the recently introduced 50 km women's racewalk event. Finally, Inoue et al. highlighted the impact of sex, performance level, and substantial speed reductions on pacing in a 24-h ultramarathon. This reinforces the need for future studies shedding more light on some of the factors influencing pacing strategies during official IAAF race formats.

MOVING FORWARD

IAAF Council awarded Eugene, USA, the 2021 IAAF World Championships. With the Doha meeting behind us, Eugene is already working with the IAAF to research innovative solutions for competition timing, scoring, measurement, and television production, using the latest technology. The IAAF is also determined to further accelerate the growth of women's athletics and Paralympics champions. This may in turn drive the development of new knowledge, using an integrative sports science approach, to improve performance of special athletic populations preparing major competitions (Tokyo 2020 Olympic and Paralympic games). On 12 October 2019, Eliud Kipchoge became the first human in history to break the 2-h marathon barrier (albeit in a non-official event). This would not have been possible without maximizing some of the factors—i.e., pacing strategy, running mechanics, and weather conditions—that formed the core of this Research Topic. As confirmed by this Research Topic, athletics continue to generate considerable interest globally. In this context, *Frontiers in Sport and Active Living* through its partnership with the Health and Science Department of the IAAF represents an ideal platform to disseminate new knowledge.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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ORIGINAL RESEARCH
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Relation of Team Size and Success With Injuries and Illnesses During Eight International Outdoor Athletics Championships

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Introduction: The number of injuries and illnesses during major athletics championships vary according to sex and discipline. They may also differ between countries (national teams) given the differences in training, medical care, nutrition, lifestyle habits, and in travel to the championships. In addition, injuries and illnesses may influence the performance during the championships. Therefore, the aim was to analyse the differences in the injury and illness occurrence during international outdoor athletics championships with regards to the athlete's country, as well as establishing the potential relationships with the success of the country during the respective championships.

Method: The national medical teams and the local organizing committee physicians reported all injuries and illnesses daily on a standardized injury and illness report form during 4 World and 4 European outdoor championships from 2007 to 2018. Results were presented as number of registered athletes, injuries, illnesses and medals (absolute and per 1000 registered athletes), and for countries of different team size.

Results: During these 8 championships, a total of 219 different countries participated with a total of 13059 registered athletes who incurred 1315 injuries and 550 illnesses. The number of injuries and illnesses per championships varied between countries. Countries with higher numbers of registered athletes had a higher number of injuries and illnesses, as well as a higher number of medals and gold medals. There were significant positive correlations between number of injuries/illnesses and number of registered athletes, medals, gold medals. Injury and illness numbers per 1,000 registered athletes differed between countries and team sizes. Analyzing country participation grouped according to the number of registered athletes, there were significant negative correlations between injury/illness and medals/gold medals per 1,000 registered athletes.

Conclusions: Given the correlation between health problems and country size, we suggest that medical services provision and staff should be adapted to the team size. In groups of different country team sizes, lower number of injuries and illnesses per registered athletes were correlated with higher number of medals and gold medals per registered athletes, which can support that injury and illness prevention should be recognized as a win-win performance-prevention strategy.

Keywords: health promotion, sports injury prevention, illness prevention, injury and illness surveillance, track and field, top-level athletes, injury risk

INTRODUCTION

Several variables can influence the athlete's performance (Morin et al., 2012; Zaras et al., 2016; Siart et al., 2017; Boccia et al., 2019; Gross et al., 2019; Loturco et al., 2019; Melin et al., 2019). Among them, being healthy, without any injury or illness, seems to be an important one (Hanstad et al., 2011; Hägglund et al., 2013; Raysmith and Drew, 2016; Drew et al., 2017). In male professional football, higher injury incidence and/or severity and lower match availability had a significant negative influence on performance in league play and in European cups (Hägglund et al., 2013). Raysmith and Drew (2016) reported that reduced participation in training due to injury and/or illness was associated with performance failure during major international athletics championships. In their systematic review, Drew et al. (2017) concluded that there was strong evidence that increased availability of team members/athletes decreased the risk of failure, and pre-competition and in-competition injuries both were associated with increased risk of failure. Finally, high illness rates were reported to be associated with the poor performance of the Norwegian team during the 2006 Winter Olympic Games (Hanstad et al., 2011). Since, currently only one study (Raysmith and Drew, 2016) analyzed relationships between injury/illness and performance in athletics, there is a need to improve this knowledge, especially in the context of major athletics championship. In addition, a potential relationship between health and performance in sport underscores the need for better understanding of injuries and illnesses, and for the development and implementation of prevention strategies (van Mechelen et al., 1992; Edouard et al., 2011, 2015a, 2018).

Several studies have analyzed the number and incidence of injuries and illnesses during major athletics championships (Alonso et al., 2009, 2010, 2012, 2015; Edouard et al., 2013, 2014a,b, 2015b,c, 2016a, 2019b; Feddermann-Demont et al., 2014; Timpka et al., 2017; Edouard et al., under revision). Feddermann-Demont et al. (2014) reported that on average 81 injuries per 1000 registered athletes occurred during 13 international championships. The number of injuries per registered athletes varied between different types of championships: higher for World than European championships, higher for outdoor than indoor championships, higher for adult than youth/junior championships) (Feddermann-Demont et al., 2014). In addition, Edouard et al. (2015b) reported that male athletes had 25% more injuries during 11 international athletics outdoor and indoor championships than female athletes. For both genders, the highest number of injuries per 1,000 registered athletes were observed in combined events (i.e., decathlon for male and heptathlon for female athletes during outdoor championships, and heptathlon for male and pentathlon for female athletes during indoors championships (Edouard et al., 2009, 2010), marathon and long distances (Edouard et al., under revision). Regarding illnesses, during 11 international championships including outdoors and indoors, 43 illnesses per 1,000 registered athletes were reported with significantly higher values for outdoor compared to indoor championships, and for endurance compared to explosive disciplines, without significant differences between male and female athletes (Edouard et al., 2019a,b).

These studies analyzed the occurrence of injuries and illnesses during major athletics championships with regard to the type of championships (outdoor vs. indoor), the athlete's sex (male vs. female athletes), and/or the athletics disciplines (endurance vs. explosive, or the nine athletics disciplines) (Alonso et al., 2009, 2010, 2012, 2015; Edouard et al., 2013, 2014a,b, 2015b,c, 2016a, 2019b; Feddermann-Demont et al., 2014; Timpka et al., 2017; Edouard et al., under revision). However, many other factors can also influence the occurrence of injuries and illnesses, given their multifactorial nature (van Mechelen et al., 1992; Meeuwisse et al., 2007; Bittencourt et al., 2016). One potential factor could be the home country of the athlete, since the training, physical conditioning, preparation of championships, medical care and availability, nutrition, lifestyle, culture, etc. may all vary between countries, and these differences may influence the risk of injuries and/or illnesses. In addition, international athletics championships often take place outside of the athlete's home country, and thus causing different travel requirements. Traveling may influence the risk of injuries and illnesses through travel itself, jet lag, changes in nutritional habits (foods and fluids), changes in environmental conditions (temperature, humidity, pollution, altitude, etc.), endemic pathogens, sanitation standards, and/or cultures different to the athlete's home country (Schwellnus et al., 2012; Fowler, 2016; Soligard et al., 2016; Mahadevan and Strehlow, 2017; Lohr et al., 2018; Schwellnus, 2019).

In this context, the aim of the present study was to analyse the differences between countries in the occurrence of injury and illness during international outdoor athletics championships, and to investigate the potential relationship with the success of the country during the respective championships.

METHODS

Study Design and Procedure

We conducted a total population study analyzing the injury and illness data collected prospectively during eight international athletics outdoor championships:

– World Outdoor Championships (WOC) 2007 (Alonso et al., 2009), 2009 (Alonso et al., 2010), 2011 (Alonso et al., 2012), 2013 (Alonso et al., 2015);
– European Outdoor Championships (EOC) 2012 (Edouard et al., 2014b), 2014, 2016, 2018.

The study design, injury and illness definitions, methods and data collection procedures, were the same for all the 8 outdoor championships (Alonso et al., 2009, 2010, 2012; Edouard et al., 2013, 2014b, 2015b,c, 2016a, 2019b; Feddermann-Demont et al., 2014; Edouard et al., under revision).

Data Collection

About 1 to 2 months before each championship, all teams/countries participating in the respective championship were informed about the study objective and modalities through emails from the organizing federation to the team leaders and the medical teams. The day before the start of each championship, the detail of the study procedure and data collection was presented to medical teams during a meeting. During the period of each championship, national medical teams (physicians and/or physiotherapists) and/or local organizing committee physicians (LOC) were asked to report daily all newly incurred injuries and illnesses on standardized injury and illness report forms available in paper or in electronic format, available in several languages (English, French, German, Spanish, Russian, Arabic, Chinese). Report forms were collected daily, and if report forms were missing the medical teams and LOC were contacted again. The issue of duplicate reporting was solved by the consensus of at least two members of the research group; information from the national team physician's report was preferred over the Local Organizing Committee (LOC) physician's report.

Injury and Illness Definitions

Injuries were defined as "all musculoskeletal injuries (traumatic and overuse) and concussions newly incurred during competition or training regardless of the consequences with respect to the athlete's absence from competition or training" (Junge et al., 2008; Alonso et al., 2009; Feddermann-Demont et al., 2014; Timpka et al., 2014; Edouard et al., 2015b). Illness was defined as "any physical complaint unrelated to an injury and occurring during the championships" (Alonso et al., 2010, 2012; Edouard et al., 2013, 2014b, 2015c; Timpka et al., 2014). In cases where a single injury incident resulted in more than one injured body part and/or type of injury, each body part and/or type injury was counted as a separate injury (Edouard et al., 2015b, 2016a; Edouard et al., under revision).

Confidentiality and Ethical Approval

All participants (i.e., athletes) were informed about the study aim and modalities via flyers distributed to each individual athlete at each championships and posters displayed in several locations, and if requested, could have their data removed from the subsequent analysis at any time without consequence. All records in the injury and illness database were anonymous, i.e., they cannot be associated with individual athletes.

The study was reviewed and approved by the Saint-Etienne University Hospital Ethical Committee (IORG0004981). Given the nature of the data collection (routine usual data collection, not systematic to all participants included) and the large sample size, the written informed consent for each individual participant was not required, by the Saint-Etienne University Hospital Ethical Committee, in accordance with the national legislation and the institutional requirements.

Data Analyses

National medical team participation (number of national medical teams who returned at least one injury report form divided by the number of countries with a medical team, as not all teams may have a medical team present on site, in percentage), athletes' coverage (number of registered athletes from a country with a medical team present who participated in the injury surveillance study divided by the total number of registered athletes, in percentage), and response rate (number of report forms returned by the national medical teams participating in the injury surveillance study divided by the number of expected report forms (i.e., number of national medical teams participating multiplied by the number of championship days), in percentage) were reported according to Edouard et al. (2016b).

Descriptive data reported were the number of countries participating in at least one championships, the number of "country participation" (i.e., one country participating in one championship), and the respective numbers of registered athletes, injuries, illnesses, medals, and gold medals as well as these variables per 1,000 registered athletes (with 95% confidence intervals) for the total population (Feddermann-Demont et al., 2014; Timpka et al., 2014; Edouard et al., 2015b, 2016a, 2019b; Edouard et al., under revision).

The number of registered athletes was calculated by using the list of registered athletes provided by the International Association of Athletics Federations (IAAF) or the European Athletics Association (EAA) for each championship (i.e., if an athlete registered for more than one championship he/she counted for each championship) (Edouard et al., 2015b, 2016a, 2019b; Edouard et al., under revision). Country participations were grouped according to the number of registered athletes per country per championship: <10, 10–24, 25–49, 50–99, >100 (Junge et al., 2009; Soligard et al., 2017).

Number of medals, gold medals and country ranking were used as performance outcome (Raysmith et al., 2019). The number of medals and gold medals as well as the country ranking (i.e., ranking of the country at the championship according to the number of gold, silver and bronze medals) for each championship and country was collected using the IAAF (https://www.iaaf.org/home) and EAA (https://www.european-athletics.org) websites.

Pearson's correlation tests, or Spearman's correlation tests when distribution normality was not observed, were used to determine the correlation coefficient and their significance. Significance was accepted at $p < 0.05$. The correlation coefficients were interpreted using Hopkin's threshold: $r = 1$: perfect; $1 > r \geq 0.90$ nearly perfect; $0.90 > r \geq 0.70$ very large; $0.70 > r \geq 0.50$: large; $0.50 > r \geq 0.30$: moderate; $0.30 > r \geq 0.10$: small; $0.10 > r$: trivial (Hopkins, 2002). Data were analyzed using Excel (Office, Microsoft®, 2017) and JASP (JASP Team software, Version 0.8.5.1, University of Amsterdam, Netherlands).

RESULTS

On average, 90.2% of all national medical teams, covering 81.9% of registered athletes, participated in the injury and illness surveillance project, and returned 90.5% of the expected report forms. No athlete refused to allow his/her data to be used for scientific research.

A total of 219 different countries participated in at least one of the eight international outdoor championships. All five continents were represented: 55 (25.1%) countries from Africa, 45 (20.5%) from North and South America, 46 (21.0%) from Asia, 53 (24.2%) from Europe, and 20 (9.1%) from Oceania. 20.5% ($n = 45$) of countries participated in all eight championships, three (1.4%) in seven, two (0.9%) in six, 134 (61.2%) in four, 21 (9.6%) in three, nine (4.1%) in two, and five (2.3%) one. This resulted in a total of 1015 country participations.

A total of 13059 athletes registered at the eight championships. The number of registered athletes per country and championship ranged from 1 to 138. For most of the country participations ($n = 691$; 68.1%), the number of registered athletes in a championship was below ten. It was between 10 and 24 athletes for 14.7% country participations, 25 to 49 (10.3%), 50 to 99 (5.6%), and ≥100 (1.3%) (**Table 1**).

A total of 1,315 injuries and 550 illnesses were reported during the eight championships. Between 0 and 23 injuries and between 0 and 18 illnesses were reported per country participation. The number of injuries per country participation varied from 0 to 2,000 injuries per 1,000 registered athletes, and the number of illnesses from 0 to 1,600 illnesses per 1,000 registered athletes, according to countries and championships. The number of injuries and illnesses per 1,000 registered athletes differed between country participation groups, with higher values in the group with small number of registered athletes and lower values in the group with high number of registered athletes (**Table 1** and **Figure 1**).

A total of 921 medals and 277 gold medals were won during the eight championships. Seventy-six (34.7%) countries won at least one medal, and 52 (23.7%) one gold medal. The number of medals and gold medals per 1,000 registered athletes differed between country participation groups, with higher values in the groups with higher numbers of registered athletes, and lower values in the groups with smaller numbers of registered athletes (**Table 1** and **Figure 1**).

Analyzing all country participations ($n = 1015$), significant positive correlations were observed between the number of injuries and the number of registered athletes ($r = 0.666$, $p < 0.01$, large), medals ($r = 0.545$, $p < 0.01$, large), gold medals ($r = 0.475$, $p < 0.01$, moderate), number of medals per 1,000 registered athletes ($r = 0.233$, $p < 0.01$, small), and a significant negative correlation between the number of injuries and the country ranking ($r = -0.445$, $p < 0.01$, moderate) (**Table 2**). There were significant positive correlations between the number of illnesses and the number of registered athletes ($r = 0.493$, $p < 0.01$, moderate), medals ($r = 0.348$, $p < 0.01$, moderate), gold medals ($r = 0.306$, $p < 0.01$, moderate), and a significant negative correlation between the number of injuries and the country ranking ($r = -0.281$, $p < 0.01$, small) (**Table 2**).

Analyzing country participation groups (**Table 1** and **Figure 1**), there were significant negative correlations between the number of injuries and the number of medals ($r = -0.92$, $p < 0.001$, nearly perfect) and of gold medals ($r = -0.90$, $p < 0.001$, nearly perfect) per 1,000 registered athletes, and between the number of illnesses and the number of medals ($r = -0.92$, $p < 0.001$, nearly perfect) and of gold medals ($r = -0.99$, $p < 0.001$, nearly perfect) per 1,000 registered athletes.

DISCUSSION

The main results of the present study were that (i) the number of injuries and illnesses per championship varied between countries, (ii) countries with higher number of registered athletes had a higher number of injuries and illnesses, as well as a higher number of medals and gold medals and a better country ranking, (iii) in country participations groups according to the number of registered athletes, lower number of injuries and illnesses per registered athletes were correlated with higher number of medals and gold medals per registered athletes.

Injury and Illness Rates Varied Between Countries

During major athletics championships, the numbers and rates of injury and illness differed between countries. Many parameters may have contributed to these differences, such as "environmental" factors (training, nutrition, availability of medical services, travel to competition etc.) and the individual athlete's intrinsic characteristics. Moreover, these differences could be due to methodological aspects, e.g., differences in injury/illness surveillance participation, response rate, and willingness to provide injury/illness data between countries/medical teams.

By grouping our data according to the number of registered athletes per country participation, we found a significant correlation between the number of injury/illness per 1,000 registered and the number of registered athletes per country participation: countries with higher numbers of registered athletes in a championship reported lower injury/illness rates (**Figure 1**). This almost linear inverse relation between the size of the teams and injury rates has also been reported for the Summer Olympic Games 2008 (Junge et al., 2009), 2012 (Engebretsen et al., 2013), and 2016 (Soligard et al., 2017), and for the illness rates during the Summer Olympic Games

TABLE 1 | Number of countries participating in at least one championships, number of "country participation" (i.e., one country participating in one championship), numbers of registered athletes, injuries, illnesses, medals and gold medals, as well as injuries, illnesses, medals and gold medals per 1,000 registered athletes (with 95% confidence intervals) according to the number of registered athletes for each country participation (i.e., <10, 10–24, 25–49, 50–99, >100).

	Number of athletes per country participation					
	<10	**10–24**	**25–49**	**50–99**	**>100**	**All**
NUMBER OF (n (%))						
Countries	183 (83.6)	46 (21.0)	37 (16.9)	18 (8.2)	4 (1.8)	219* (100.0)
Country participation	691 (68.1)	149 (14.7)	105 (10.3)	57 (5.6)	13 (1.3)	1015 (100.0)
Registered athletes	1712 (13.1)	2305 (17.7)	3748 (28.7)	3800 (29.1)	1494 (11.4)	13059 (100.0)
All injuries	218 (16.6)	252 (19.2)	408 (31.0)	340 (25.9)	97 (7.4)	1315 (100.0)
All illnesses	109 (19.8)	102 (18.5)	154 (28.0)	160 (29.1)	25 (4.5)	550 (100.0)
All medals	50 (5.4)	86 (9.3)	297 (32.2)	295 (32.0)	193 (21.0)	921 (100.0)
Gold medals	16 (5.8)	20 (7.2)	91 (32.9)	87 (31.4)	63 (22.7)	277 (100.0)
NUMBER PER 1,000 REGISTERED ATHLETES (95%CI)						
All injuries	127.3 (111.5 to 143.1)	109.3 (96.6 to 122.1)	108.9 (98.9 to 118.8)	89.5 (80.4 to 98.5)	64.9 (52.4 to 77.4)	100.7 (95.5 to 105.9)
All illnesses	63.7 (52.1 to 75.2)	44.3 (35.9 to 52.6)	41.1 (34.7 to 47.4)	42.1 (35.7 to 48.5)	16.7 (10.2 to 23.2)	42.1 (38.7 to 45.6)
All medals	29.2 (21.2 to 37.2)	37.3 (29.6 to 45.0)	79.2 (70.6 to 87.9)	77.6 (69.1 to 86.1)	129.2 (112.2 to 146.2)	70.5 (66.1 to 74.9)
Gold medals	9.3 (4.8 to 13.9)	8.7 (4.9 to 12.5)	24.3 (19.4 to 29.2)	22.9 (18.1 to 27.7)	42.2 (32.0 to 52.4)	21.2 (18.7 to 23.7)

**the number of countries for "all" is different than the sum of the number of countries reported in each country participation group, since the number of athletes registered could have differed in the same country between championships.*

There were significant negative correlations between the number of injuries per 1,000 registered athletes and the number of medals per 1,000 registered athletes ($r = -0.92$, $p < 0.001$, nearly perfect) and of gold medals per 1,000 registered athletes ($r = -0.90$, $p < 0.001$, nearly perfect), and between the number of illnesses per 1,000 registered athletes and the number of medals per 1,000 registered athletes ($r = -0.92$, $p < 0.001$, nearly perfect) and of gold medals per 1,000 registered athletes ($r = -0.99$, $p < 0.001$, nearly perfect).

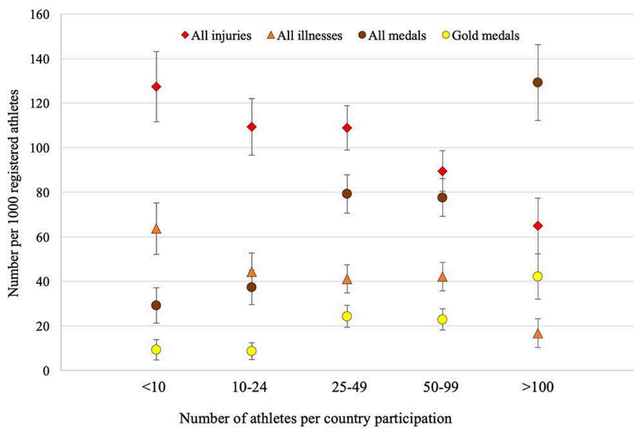

FIGURE 1 | Number of injuries, illnesses, medals and gold medals per 1,000 registered athletes (and 95% confidence interval) per country participation according to the number of registered athletes for each country participation (i.e., <10, 10–24, 25–49, 50–99, >100). The number of injuries per 1,000 registered athletes correlated significantly negative with the number of medals ($r = -0.92$, $p < 0.001$, nearly perfect) and with the number of gold medals ($r = -0.90$, $p < 0.001$, nearly perfect) per 1,000 registered athletes. The number of illnesses per 1,000 registered athletes correlated significantly negative with the number of medals ($r = -0.92$, $p < 0.001$, nearly perfect) and of gold medals ($r = -0.99$, $p < 0.001$, nearly perfect) per 1,000 registered athletes.

2012 (Engebretsen et al., 2013) and 2016 (Soligard et al., 2017). The fact that small teams come to the championships without any medical team, and may have difficulties accessing health professionals in the preparation for championships might be a possible explanation. However, such results require further research to better understand these differences between countries in injury/illness rates (e.g., analyzing, for small teams, the availability of medical services before the championships, and the behavior regarding the use of medical services during the championships), in order to design appropriate injury/illness prevention measures.

"Nothing Ventured, Nothing Gained"

Our study revealed a significant positive correlation between the number of registered athletes per countries and the number of (gold) medals won, i.e., countries with a higher number of registered athletes were more likely to win medals during major international championships. In addition, a significant positive correlation between the number of registered athletes and the number of injuries and illnesses were observed, i.e., countries with a higher number of registered athletes were most likely to have injured or sick athletes in their teams. Thus, when increasing the number of athletes, it may increase the chance to have top-level athletes who can win medals, but also may increase the risk of incurring injuries and illnesses in the team. As a practical implication, we can suggest that larger teams should prepare for the championships with appropriate medical services and staff to encompass the higher risk of health problems.

Lower Injury and Illness Rates Seem to Allow Higher Performance During Athletics Championships

Previous studies reported a relationship between health and sport performance (Hanstad et al., 2011; Hägglund et al., 2013; Raysmith and Drew, 2016; Drew et al., 2017). There was strong evidence that injury and/or illness can impact sporting success, especially increased availability of team members/athletes decreased the risk of failure, and pre-competition and

TABLE 2 | Correlations between the numbers of injuries and illnesses with the numbers registered athletes, medals and gold medals, and country ranking, as well as correlations of these numbers reported per 1,000 registered athletes.

	Number of registered athletes	Country ranking	Number of medals	Number of gold medals	Number of medals per 1,000 registered athletes	Number of gold medals per 1,000 registered athletes
NUMBER OF						
All injuries	**$r = 0.666$, $p < 0.01$, large**	**$r = -0.445$, $p < 0.01$, moderate**	**$r = 0.545$, $p < 0.01$, large**	**$r = 0.475$, $p < 0.01$, moderate**	**$r = 0.233$, $p < 0.01$, small**	$r = 0.145$
All illnesses	**$r = 0.493$, $p < 0.01$, moderate**	**$r = -0.281$, $p < 0.01$, small**	**$r = 0.348$, $p < 0.01$, moderate**	**$r = 0.306$, $p < 0.01$, moderate**	$r = 0.118$	$r = 0.085$
NUMBER PER 1,000 REGISTERED ATHLETES						
All injuries	$r = -0.019$	$r = -0.003$	$r = 0.003$	$r = 0.002$	$r = 0.100$	$r = 0.025$
All illnesses	$r = -0.063$	$r = 0.117$	$r = -0.047$	$R = -0.034$	$r = -0.046$	$r = -0.001$

Significant correlations are highlighted in bold.

in-competition injuries both were associated with increased risk of failure in reaching the performance goals (Drew et al., 2017). In a population of 33 international track and field athletes followed during 5 seasons, the loss in training availability due to injury and/or illness was associated with performance failure during major international championships (Raysmith and Drew, 2016). Our present study supports the relationships between injury and illness and performance during major international championships. It also provides some additional preliminary findings on the relationships of country size (i.e., number of registered athletes per championships) with health problem and performance. Consequently, we fully agree with practical recommendations of Drew et al. (2017):

- "Athlete health should be prioritized as a component of the integrated performance system;
- Multiple stakeholders (e.g., clinician, coach, sport scientist, the athlete) are accountable for both performance and the health;
- Sacrificing an athlete's safety resulting in injury or illness may also result in lower performance;
- Performance cannot be researched without consideration of the health status of the athlete both during competition and the period prior."

Injury and illness prevention should be seen and included as a win-win performance-prevention strategy (Edouard et al., 2019a,b). These injury and illness prevention measures should be especially implemented in period prior to a major event, within the 6-month prior as suggested by Raysmith and Drew (2016), or at least during the month prior to the major event as suggested several studies (Alonso et al., 2015; Edouard et al., 2015c; Timpka et al., 2017), and during the event itself as suggested by our present results. This could also be one way to improve adherence, compliance and engagement in injury and illness prevention programmes (Drew et al., 2017).

Methodological Considerations

To our best knowledge, this is the first study to analyse the relationships between injuries/illnesses and performance success during major athletics championships. Although some limitations detailed below should be acknowledged, these preliminary results allow hypothesizing that injury and illness prevention could be a way of improving athletics performance. These present findings extend those from previous epidemiological studies during international athletics championships (Alonso et al., 2009, 2010, 2012, 2015; Edouard et al., 2014b, 2015b, 2016a, 2019b; Feddermann-Demont et al., 2014; Timpka et al., 2017; Edouard et al., under revision) by showing a close relationship between health and performance of the athletes. These results are based on a good methodological quality, regarding team participation and response rates (Edouard et al., 2016b), and on a large sample size (219 countries, 13,059 registered athletes, 1,315 injuries and 550 illnesses) allowing more representative results.

In addition to the limitations previously discussed (Alonso et al., 2009, 2010, 2012; Edouard et al., 2013, 2014b, 2015b,c, 2016a, 2019b; Feddermann-Demont et al., 2014; Edouard et al., under revision), others should be acknowledged. The country participation (i.e., one country participating in one championship) means that some countries and athletes were counted more than once, e.g., in the groups of country participation according to the number of registered athletes (due to multiple participation of countries and athletes in several championships). The differences in numbers and rates of injuries/illnesses could be caused by different reporting of national medical teams. Especially, countries with a small number of registered athletes often do not have sufficient medical staffs and use the opportunity to consult the LOC medical centers for their injuries or illnesses. We reported the number of injuries and illnesses, which is different from the number of injury events, and of injured and sick athletes. Injury and illness information should not be interpreted as risk indicators at the level of individual athletes (Edouard et al., 2019b; Edouard et al., under revision). We chose number of medals and country ranking as sports performance outcome, which relates to the country and not to the individual athletes (e.g., metrics parameters, intra-personal parameters) (Drew et al., 2017; Raysmith et al., 2019). We acknowledge that numerous factors (e.g., physical, physiological, psychological, and/or technical aspects), in addition to injury and illness, may influence a performance outcome (Raysmith and Drew, 2016). The number of (gold) medals per country per championship collected on the IAAF and EAA websites for the present study could have changed from the time of the competition (and time of the injury/illness data collection), since some athletes who won medals in the championships have been excluded *a posteriori* because of doping.

CONCLUSIONS

This study showed that the number of injuries and illnesses during eight major international athletic championships varied between countries with different numbers of registered athletes. Larger countries reported higher number of injuries and illness, and small countries reported higher injury and illness rates. Thus, medical services provision and staff need to be adapted to the size of the team, and small teams may need special support in their medical services provision and staff. Country participations with a higher number of registered athletes reported fewer injuries and illnesses per registered athlete, and won more medals and gold medals per registered athlete. This highlights that injury and illness prevention should be included as a win-win performance-prevention strategy.

DATA AVAILABILITY

The raw data supporting the conclusions of this manuscript will be made available by the authors, after explicit and justified request, to any qualified researcher.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the study was reviewed and approved by the Saint-Etienne University Hospital Ethical Committee (IORG0004981). Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

PE: conceived and designed the present analysis. PE and PB: performed data collection. PE and LN: analyzed the data. PE, PB, and AJ: interpreted the results. PE: drafted the manuscript and prepared the table/figure. PE, AR, LN, VG, PB, and AJ: edited, critically revised the manuscript, and approved the final version.

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The Science Behind Competition and Winning in Athletics: Using World-Level Competition Data to Explore Pacing and Tactics

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The purpose of this study was to examine whether World Championship and Olympic medallist endurance athletes pace similarly to their race opponents, where and when critical differences in intra-race pacing occur, and the tactical strategies employed to optimally manage energy resources. We analyzed pacing and tactics across the 800, 1,500, 5,000, 10,000 m, marathon and racewalk events, providing a broad overview for optimal preparation for racing and pacing. Official electronic splits from men's ($n = 275$ performances) and women's ($n = 232$ performances) distance races between 2013 and 2017 were analyzed. Athletes were grouped for the purposes of analysis and comparison. For the 800 m, these groups were the medalists and those finishing 4th to 8th ("Top 8"). For the 1,500 m, the medalists and Top 8 were joined by those finishing 9th to 12th ("Top 12"), whereas for all other races, the Top 15 were analyzed (those finishing 9th to 15th). One-way repeated measures analysis of variance was conducted on the segment speeds ($p < 0.05$), with effect sizes for differences calculated using Cohen's d. Positive pacing profiles were common to most 800 m athletes, whereas negative pacing was more common over longer distances. In the 1,500 m, male medalists separated from their rivals in the last 100 m, whereas for women it was after 1,200 m. Similarly, over 5,000 m, male medalists separated from the slowest pack members later (4,200 m; 84% of duration) than women (2,500 m; 50% of duration). In the 10,000m race, the effect was very pronounced with men packing until 8,000 m, with the Top 8 athletes only dropped at 9,600 m (96% of duration). For women, the slowest pack begin to run slower at only 1,700 m, with the Top 8 finishers dropped at 5,300 m (53% of duration). Such profiles and patterns were seen across all events. It is possible the earlier separation in pacing for women between the medalists and the other runners was because of tactical racing factors such as an early realization of being unable to sustain the required speed, or perhaps because of greater variation in performance abilities.

Keywords: athletics, pacing, race performance, running, tactics

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INTRODUCTION

Every two years, the International Association of Athletics Federations (IAAF) World Championships are held. This provides us with an ideal opportunity to provide up-to-date scientific knowledge on aspects relevant to performance, competition and winning, which will clearly be relevant to athletes and coaches taking part in these and other similar championships. Specific problems encountered by athletes in competition, particularly in the longer race events, relate to distributing available energy over a race (i.e., pacing) and how to optimally engage in interpersonal competition (i.e., tactics). Both aspects have been found to be decisive factors in athlete performance (Konings and Hettinga, 2018a). Athletes are required to decide continuously about how and when to invest their limited energy resources over time to win the race (Edwards and Polman, 2013; Smits et al., 2014) not only when racing alone, but also when racing against other competitors (Hettinga et al., 2017), as occurs in IAAF World Championships. When in competition, opponents and other environmental factors influence motivation, attentional focus (perception), the ability to tolerate fatigue and pain, positioning, drafting, falls risk, and collective behavior, and hence race performance cannot be examined in isolation. Therefore, it is important to analyze real-life competitive events, and sport environments are nowadays ideally suited to provide us with large datasets on how humans behave, decide and perform under physically challenging circumstances (Hettinga, 2018). In Olympic and World Championship short track speedskating, this has already been shown to be successful and resulted in a better understanding of the impact of tactics (Konings et al., 2016a; Noorbergen et al., 2016; Konings and Hettinga, 2018b), preceding qualifying races (Konings and Hettinga, 2018c), and different competitive environments (Konings and Hettinga, 2018d) on pacing and performance.

In athletics, several studies have focused on world record performances, paced races in Diamond League meets, and the mass fields in city marathons (Deaner et al., 2015; Díaz et al., 2018; Filipas et al., 2018). By contrast, the first studies analyzing pacing and tactics in both men and women using official timing split data across multiple IAAF World Championships have only been completed recently (Hanley, 2013, 2016; Filipas et al., 2019; Hanley et al., 2019). The results confirmed the potential of rigorous analysis of competition data across endurance races, finding that successful middle-distance athletes generally separated themselves from slower athletes in the final 200 m, not by speeding up, but by avoiding slowing compared with competitors. Pacing variability was high compared with world records and longer distance events, especially in the finals, showing that athletes must cope with varied pace and surges. It was also recently found that World Championship middle-distance finalists were racers, rather than pacers (Hanley and Hettinga, 2018) and approached each round with a strategy of winning, rather than necessarily focusing on optimizing energy conservation (Brown, 2005).

Although recent 800 and 1,500 m world-class race data have previously been explored in quite some detail (Hanley and Hettinga, 2018; Hanley et al., 2019), for the longer distances of 5,000, 10,000 m, marathon and 20 and 50 km racewalks, the most recent championship performances have not yet been included or have relied on low resolution data (e.g., every 1,000 m in the track events, and every 5 km in the road events). For the 5,000 and 10,000 m, 1,000-m split analyses have been conducted up until 2017 (Filipas et al., 2019), but 100-m splits are available for the very recent Olympic Games and World Championships of 2013, 2016, and 2017, which could provide additional insights into variability of race performances as completed for the middle-distances (Hanley and Hettinga, 2018; Hanley et al., 2019). For the marathon, data have been analyzed using 5-km split data from 2011 up until 2015 (Hanley, 2016). Race data from 2016 and 2017 are now available and can be included for analysis to provide more insights into developments of marathon performance throughout the last two decades, and more specifically, in relation to the current crop of world-class distance athletes. This point is particularly pertinent for coaches as pacing can be strongly dictated by the presence of a single contemporary, uniquely talented athlete (Sandford et al., 2018). Lastly, the 20 and 50 km racewalks have been analyzed using 5-km split times including data from 1999 to 2011 (Hanley, 2013), but more recent data are available to us, and with higher resolutions of 1-km or 2-km splits. The ban on Russian athletes competing (with the exception of Authorized Neutral Athletes) since 2015 has had its biggest effect on racewalking as, notwithstanding some subsequent disqualifications, Russian athletes finished first in 11 of the 15 racewalk events held at the World Championships from 2005 to 2013, and changes in pacing profiles might have occurred since the previous analyses. Most notably, no women's data have been analyzed for the 50 km racewalk before, as this event was first held at a global championship in 2017. High-resolution 1-km split data from this event were made available to us by the official timing company to analyze and will provide new insights into women's athletics.

In the current paper, we will bring together all up-to-date available data from Olympic and World Championship finals in the 800, 1,500, 5,000, 10,000 m, marathon, 20 and 50 km racewalk to explore the science behind competition and winning in world-level championships. We will include recent data in our analyses to explore pacing and tactics of both men and women athletes, and we will discuss these in the specific context of global championships to provide athletes and coaches with valuable insights and advice to prepare for competition.

MATERIALS AND METHODS

Official electronic finishing and split times for the men's and women's middle-distance, long-distance and racewalk finals at the IAAF World Championships in 2013 and 2017, as well as the Olympic Games in 2016, were obtained from the open-access IAAF website (IAAF, 2019), published results (Almeida, 2016), and directly from the official timing company for the IAAF World Championships, SEIKO (with permission from the IAAF). Split data for each 100-m segment of the 800, 1,500, 5,000 and 10,000 m finals were analyzed; for the 800 m, high-resolution split data from the 2016 Olympic Games were not available. For the marathon, race split times were obtained for each 5 km, halfway (21.098 km) and the finish (42.195 km). For convenience, the final segment distance in the marathon is described in this study as 2.2 km. For the 20 km racewalks, split data for each 2 km loop have been analyzed, whereas for the 50 km racewalks, split data for each 5-km segment have been analyzed. The women's 50 km racewalk was first held in 2017, with its late addition meaning very few athletes ($n = 7$) took part. Because we were able to obtain 1-km splits for each racewalk event at the 2017 IAAF World Championships courtesy of SEIKO and the IAAF, we have also included analyses of these specific races at this higher 1-km resolution. All split data were recorded using transponders carried by the athletes (usually as part of their number bib) that used radio-frequency identification (RFID); finishing times were recorded using official electronic timing devices that were accurate to 1/1000 s (IAAF, 2015).

In each race, athletes were grouped for the purposes of analysis and comparison. For the 800 m, these groups were the top three finishers ("medalists") and those finishing 4th to 8th ("Top 8"). For the 1,500 m, the medalists and top 8 groups were joined by those finishing 9th to 12th ("Top 12"), whereas for all other races, the groups were the medalists, Top 8 and Top 15 (i.e., those finishing 9th to 15th). Athletes who have been subsequently disqualified since the championships (e.g., for doping offenses) have not been included. Hence, an athlete finishing 9th behind a subsequently disqualified athlete, for example, has been considered to have finished 8th. If split data were missing for an athlete at any distance, that athlete has not been included in the study (i.e., one woman finishing 15th in the 10,000 m and one man finishing 15th in the marathon). Overall, 275 men's and 232 women's performances were analyzed, which included performances by 102 athletes who competed in more than one championship.

Data Analysis

The study was designed as observational research in describing pacing profiles in recent world-class endurance championships in athletics. Athletes' split times were used to calculate mean speed during each 100-m, 1-km, 2-km, or 5-km segment (as appropriate) before the given split (e.g., 0–100 m was termed the 100-m segment). In the marathon, the split time for halfway (21.098 km) was also recorded. A positive split was considered to occur when an athlete ran the second half of the race in a longer time than the first, and a negative split occurred when the first half was longer (Abbiss and Laursen, 2008). To calculate whether athletes ran a positive or negative split in the 1,500 m, the 700–800-m split time was divided by two and this halved time added to the first and second 700-m segments; for all other events, halfway data were available for this purpose. To allow easier comparison between events, all running and racewalking speeds are presented as km/h. Pace variability was measured using coefficient of variation of all segments, calculated as a percentage (CV%) for each athlete's performance using the mean and standard deviation (SD) of all their segment speeds.

Statistics

One-way repeated measures analysis of variance (ANOVA) was conducted on the segment speeds, with repeated contrast tests conducted to identify changes between successive segments (Field, 2009). Greenhouse-Geisser corrections were used if Mauchly's test for sphericity was violated. Segment speeds between the two groups in the 800 m events were compared using independent t-tests, whereas one-way ANOVA with Tukey's *post-hoc* tests were conducted to compare mean segment speeds when three groups were analyzed (Field, 2009). To compare men's and women's pacing profiles, individuals' speeds for each section were expressed as a percentage of their mean speed for the whole

TABLE 1 | Mean (±SD) finishing times for each group of men and women athletes in each event.

	Medalists	Top 8	Top 12/15
MEN			
800 m	1 : 44.24 (± 0.80)	1 : 45.48 (± 1.04)	
1,500 m	3 : 40.26 (± 7.48)	3 : 41.19 (± 7.06)	3 : 43.20 (± 6.59)
5,000 m	13 : 21.37 (±13.40)	13 : 24.30 (±12.46)	13 : 35.25 (±15.79)
10,000 m	27 : 05.96 (±13.94)	27 : 12.94 (±13.44)	27 : 30.80 (±12.89)
Marathon	2 : 09 : 42 (±0 : 39)	2 : 11 : 22 (±0 : 33)	2 : 13 : 24 (±0 : 55)
20 km racewalk	1 : 19 : 58 (±1 : 13)	1 : 20 : 38 (±1 : 16)	1 : 21 : 33 (±1 : 18)
50 km racewalk	3 : 39 : 47 (±2 : 42)	3 : 43 : 26 (±1 : 46)	3 : 47 : 46 (±1 : 56)
WOMEN			
800 m	1 : 56.80 (± 1.10)	1 : 58.59 (± 0.97)	
1,500 m	4 : 05.28 (± 3.52)	4 : 07.18 (± 3.80)	4 : 09.86 (± 4.05)
5,000 m	14 : 40.02 (± 9.55)	14 : 57.07 (± 9.05)	15 : 21.83 (±20.19)
10,000 m	30 : 21.17 (±40.61)	30 : 54.67 (±33.05)	31 : 50.09 (±30.72)
Marathon	2 : 26 : 00 (±1 : 28)	2 : 29 : 12 (±3 : 38)	2 : 32 : 09 (±3 : 59)
20 km racewalk	1 : 27 : 40 (±1 : 03)	1 : 29 : 02 (±0 : 44)	1 : 30 : 47 (±0 : 49)

Times are presented as min:s for the 800, 1,500, 5,000 and 10,000 m, and as h:min:s in the marathon and racewalks.

TABLE 2 | Mean (±SD) CV% for each group of men and women athletes in each event.

	Medalists	Top 8	Top 12/15
MEN			
800 m	5.5 (±0.9)	6.4 (±1.6)	
1,500 m	9.2 (±4.5)	9.0 (±4.2)	8.5 (±4.4)
5,000 m	8.5 (±1.7)	7.5 (±2.2)	5.9 (±1.9)
10,000 m	5.1 (±0.5)	4.1 (±0.7)	3.2 (±0.6)
Marathon	2.8 (±1.1)	2.6 (±1.0)	3.5 (±2.2)
20 km racewalk	1.7 (±0.7)	1.4 (±0.5)	1.9 (±0.9)
50 km racewalk	1.6 (±0.7)	1.7 (±0.9)	2.5 (±1.5)
WOMEN			
800 m	4.6 (±1.6)	4.9 (±1.2)	
1,500 m	9.7 (±3.0)	8.8 (±3.1)	8.0 (±2.7)
5,000 m	6.9 (±1.6)	5.7 (±1.5)	4.5 (±1.5)
10,000 m	4.9 (±1.8)	4.1 (±1.6)	3.8 (±1.2)
Marathon	2.6 (±1.1)	3.0 (±1.6)	2.9 (±1.3)
20 km racewalk	3.7 (±0.9)	2.6 (±0.7)	1.8 (±0.8)

race, and grouped together: medalists and Top 8 in the 800 m; medalists, Top 8 and Top 12 in the 1,500 m; and medalists, Top 8 and Top 15 in all other events. These percentage data were arcsine transformed for the purposes of statistical analysis (Hanley, 2018) and compared using independent t-tests. Statistical significance was accepted as $p < 0.05$. 95% confidence intervals (95% CI) were also calculated (Field, 2009). Effect sizes for differences between successive segments and between groups for each segment were calculated using Cohen's d (Cohen, 1988), rounded to two decimal places and considered to be either trivial ($d < 0.20$), small (0.21–0.60), moderate (0.61–1.20), large (1.21–2.00), or very large (2.01–4.00) (Hopkins et al., 2009). In all figures and tables (and the text below), differences between successive splits have been annotated only when the effect size was moderate or larger ($d \geq 0.61$) and the 95% CI did not cross zero. The distances at which differences were found between groups for segment speeds are also shown.

RESULTS

The mean finishing times for each group in each race demonstrated the world-class standard of the competitors analyzed (**Table 1**). There was higher variability in pace in the shorter events of the 800, 1,500, and 5,000 m (**Table 2**); the mean speeds for each 100-m split for each group of 800 and 1,500 m athletes (**Figure 1**) highlight the considerable variation in speed in each event. In the 800 m, the percentage differences in running time between the first and second halves (**Table 3**) show that it is the only distance with consistently slower second halves. In the men's event, all athletes ran a positive split, whereas in the

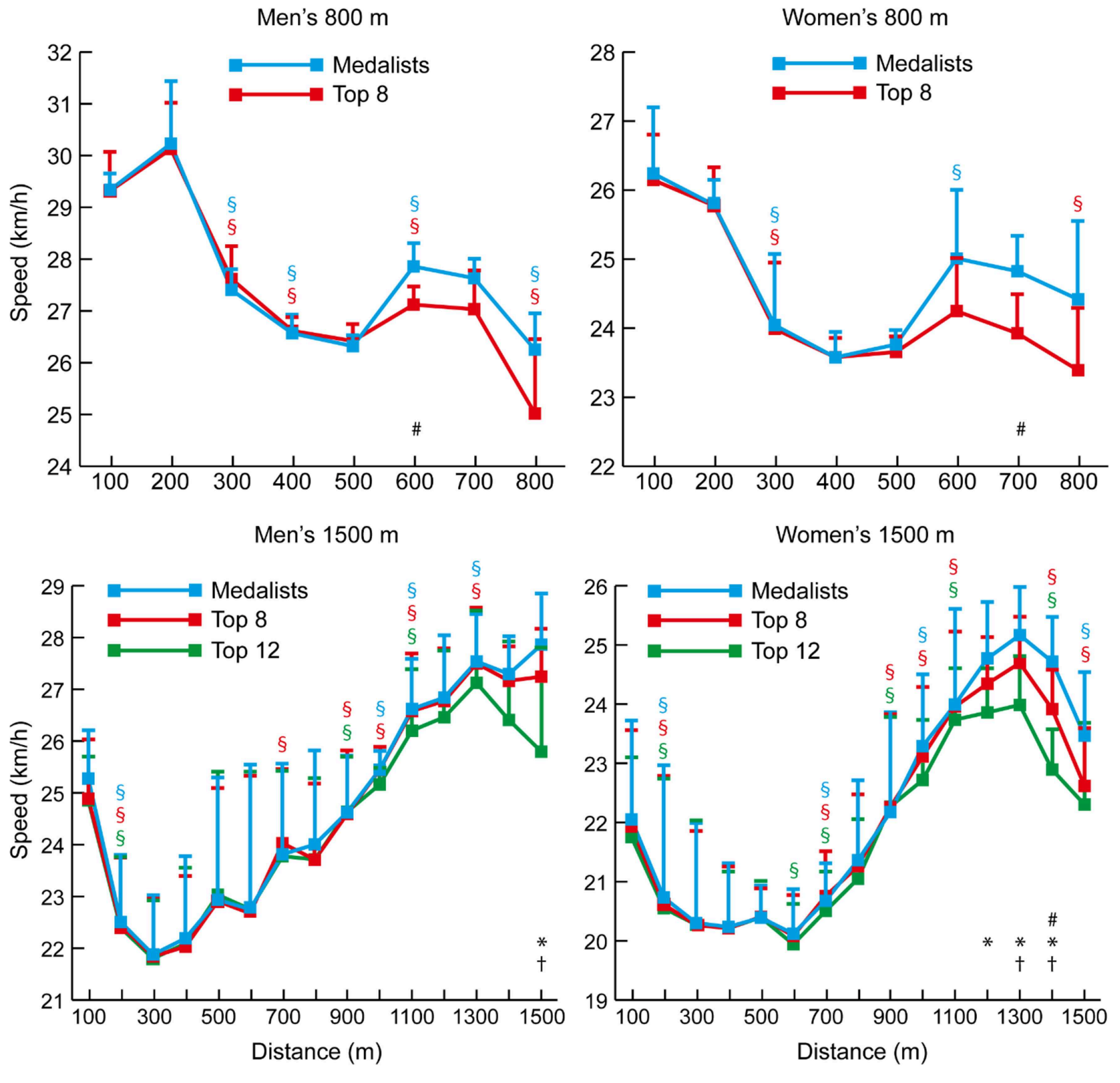

FIGURE 1 | The mean (+ SD) 100-m segment speed for each group of men and women 800 and 1,500 m athletes. Differences between successive segments ($p < 0.05$, $d \geq 0.61$) are represented by § (blue for medalists, red for Top 8, and green for Top 12). Differences in segment speed between groups ($p < 0.05$, $d \geq 0.61$) have been annotated for medalists vs. Top 8 (#), medalists vs. Top 12 (1,500 m only) (*), and Top 8 vs. Top 12 (1,500 m only) (†).

TABLE 3 | Mean (±SD) split percentages for each group of men and women athletes in each event based on halfway split and finishing times.

	Medalists	Top 8	Top 12/15
MEN			
800 m	+4.6 (±1.3)	+7.0 (±2.0)	
1,500 m	−14.9 (±9.1)	−14.7 (±8.3)	−12.8 (±9.6)
5,000 m	−8.7 (±4.5)	−8.1 (±4.6)	−5.1 (±5.2)
10,000 m	−3.4 (±1.4)	−2.6 (±1.4)	−0.7 (±1.4)
Marathon	−2.2 (±1.7)	+0.4 (±1.2)	+2.7 (±1.6)
20 km racewalk	−1.9 (±1.3)	−0.3 (±1.5)	+1.2 (±1.8)
50 km racewalk	−2.0 (±1.2)	+0.2 (±2.1)	+1.5 (±2.9)
WOMEN			
800 m	+1.4 (±3.0)	+4.1 (±3.1)	
1,500 m	−15.1 (±8.8)	−13.6 (±8.3)	−12.1 (±8.2)
5,000 m	−7.6 (±2.8)	−5.0 (±2.6)	−0.6 (±2.8)
10,000 m	−3.3 (±3.5)	−0.4 (±4.1)	+0.4 (±3.4)
Marathon	−1.7 (±2.0)	+0.5 (±4.3)	+2.2 (±2.8)
20 km racewalk	−5.7 (±1.5)	−2.3 (±2.6)	+0.0 (±1.5)

Positive values indicate positive pacing (i.e., the athletes slowed in the second half) and are indicated with a + sign for emphasis, and negative values indicate negative pacing.

women's event, two of the six medalists ran negative splits; all other 800 m women ran positive splits. By contrast, in the 1,500 m events, all men and women ran negative splits. The mean 100-m segment speed percentages for all men and all women analyzed in the 800 m and 1,500 m (**Figure 2**) showed that men had relatively faster splits in the first quarter of the 800 m ($p < 0.001$, $d = 1.64$, 95% CI = 2.56–7.00), but slower ones in the 1,500 m ($p = 0.001$, $d = 0.73$, 95% CI = 2.06–7.58). Men were relatively slower in the last 100 m of the 800 m ($p = 0.016$, $d = 1.12$, 95% CI = 1.31–11.91), but were faster in the same section in the 1,500 m ($p = 0.001$, $d = 0.99$, 95% CI = 4.16–14.26).

In general, the pacing profiles of the 5,000 m and 10,000 m races showed typical championship patterns of slightly varying pace until the final laps (**Figures 3**, **4**, respectively). This resulted in all medalists and Top 8 athletes in the men's and women's 5,000 m races running negative splits, although the fact that four of the 21 men and eight of the 20 women in the Top 15 groups did not shows the inability of these lower-finishing athletes to maintain pace with faster athletes. Similarly, all of the medalists and Top 8 athletes in the men's 10,000 m ran negative splits, but seven of the 21 men in the Top 15 group ran positive splits. Likewise, eight of the nine medalists in the women's 10,000 m ran negative splits, as well as seven of the 15 Top 8 athletes, and 13 of the 20 women who were included in the Top 15 group ran positive splits. The mean 100-m segment speed percentages for all men and all women analyzed in the 5,000 m and 10,000 m (**Figure 5**) show that there were occasional differences in the pacing profiles adopted, with men noticeably finishing relatively faster in the 5,000 m (4,200–4,800 m: $p \leq 0.003$, $d = 0.89$–1.57). It was also noticeable that the separation of groups occurred earlier in the women's races (women medalists vs. Top 15 at 2,500 m: $p = 0.007$, $d = 1.26$, 95% CI = 0.17–1.24; medalists vs. Top 8 at 2,700 m: $p = 0.027$, $d = 0.90$, 95% CI = 0.06–1.29), with men staying in a group for longer (men medalists vs. Top 15 at 4,400 m: $p = 0.013$, $d = 1.07$, 95% CI = 0.30–2.88; medalists vs. Top 8 at 5,000 m: $p = 0.004$, $d = 2.06$, 95% CI = 0.61–3.67) (**Figures 3**, **4**).

The mean speeds for each 5-km and final 2.2-km split for each group of marathon athletes show occasional and gradual increases in pace for the men until 35 km (10, 15, 25, 35 km: $p \leq 0.043$, $d = 0.65$–1.51), whereas the women seemed to adopt more even pacing throughout (**Figure 6**), especially those in the Top 8 and Top 15 groups. All men medalists and eight of the nine women medalists ran negative splits. Seven of the 15 men and 10 of the 15 women in the Top 8 groups also ran negative splits, but only one of the 20 men and seven of the 21 women in the Top 15 groups managed negative splits. As in the track races, the separation of groups occurred earlier in the women's races (medalists vs. Top 15 at 15 km: $p = 0.011$, $d = 1.08$, 95% CI = 0.09–0.79; Top 8 vs. Top 15 at 25 km: $p = 0.029$, $d = 0.83$, 95% CI = 0.04–0.92). The mean 5-km and end 2.2-km segment speed percentages for all men and all women analyzed in the marathon events (**Figure 7**) show that the men started relatively slower than the women (at 5 km: $p = 0.008$, $d = 0.68$, 95% CI = 1.27–8.14), ran the middle section faster (at 20 km: $p < 0.001$, $d = 1.16$, 95% CI = 4.53–9.54), but then slowed more in the last sections (at 42.2 km: $p = 0.001$, $d = 0.69$, 95% CI = 3.13–12.04).

The mean speeds for each 2-km split for each group of 20 km racewalkers (**Figure 8**) also show that the women's groups were separated earlier than in the men's race (women medalists vs. Top 15 at 10 km: $p = 0.005$, $d = 1.27$, 95% CI = 0.08–0.50; Top 8 vs. Top 15 at 8 km: $p = 0.011$, $d = 1.12$, 95% CI = 0.04–0.32), and that after 6–8 km the Top 15 group were unable to increase pace to keep up with the medalists and Top 8 athletes, with the medalists similarly being able to increase pace more so than the Top 8 as the race progressed. All medalists in both men's and women's 20 km racewalks achieved negative splits, as did 10 of the 15 men and 12 of the 15 women in the Top 8 groups. By contrast, only four of the 21 men and nine of the 21 women in the Top 15 groups racewalked negative splits. The mean 2-km segment speed percentages for all men and all women analyzed in the 20 km racewalks (**Figure 7**) shows that men started relatively faster (at 2 km: $p < 0.001$, $d = 1.38$, 95% CI = 3.99–7.77) and finished relatively slower (at 20 km: $p = 0.002$, $d = 0.68$, 95% CI = 2.27–9.75). The mean speeds for each 5-km split for each group of men's 50 km racewalkers (**Figure 8**) showed that the medalists were able to achieve near even paces for the whole race, whereas those finishing outside the medals slowed after 40 km (at 45 km: $p \leq 0.001$, $d = 0.65$–0.66). In the men's 50 km racewalk, all medalists achieved negative splits, as did most (9 out of 15) of the Top 8 group. However, only six of the 21 men in the Top 15 group achieved negative splits. The individual pacing profiles of the medalists from the 2017 IAAF World Championships, shown in **Figure 9**, highlight the individual variation in pace during the 50 km racewalk.

DISCUSSION

Although elite athlete race data have previously been explored (Hanley and Hettinga, 2018; Hanley et al., 2019), this is the first study to examine high-resolution data sampling (i.e., sector

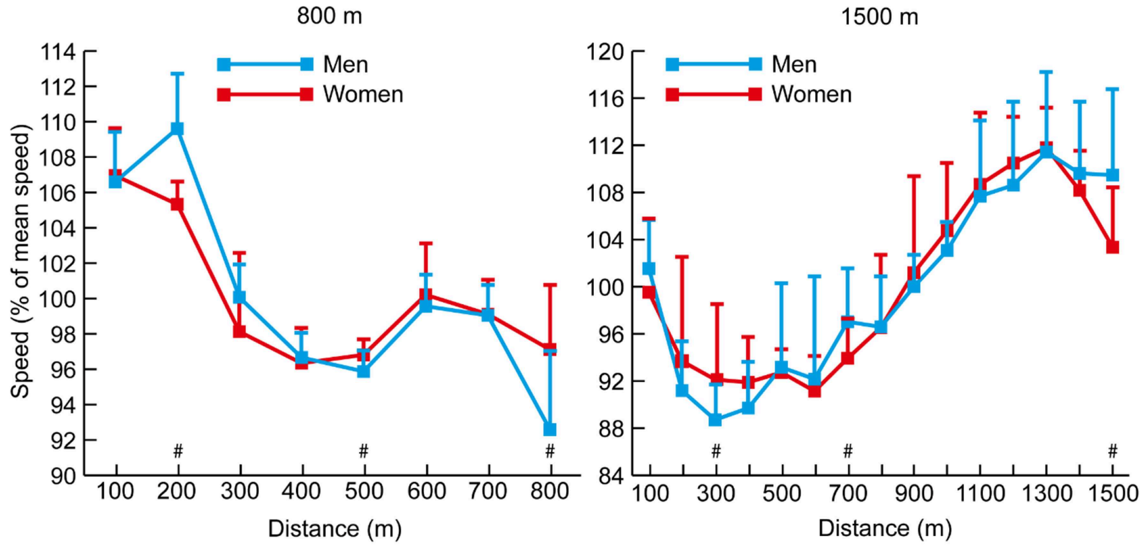

FIGURE 2 | The mean (+ SD) section speed expressed as a percentage of mean speed for all men and women in the 800 and 1,500 m events. Differences in segment speed percentage between men and women ($p < 0.05$, $d \geq 0.61$) have been annotated (#).

times) of World Championship and Olympic pacing profiles across middle-distance, long-distance and racewalk events for men and women, while including for the first time data from the recently introduced 50 km women's racewalk event. The major insights from our study demonstrate the prevalent pacing strategies employed in the different IAAF events for men and women according to their finishing positions, while also showing for the first time distinct separation points in most events where the speed profiles for medalists start to follow a different trajectory from those of other competitors. The trajectories generally show that medalists are able to maintain high speeds throughout the entire race and are still able to speed up toward the end, whereas lower-finishing athletes are able to keep up with this medal pace for a period, but then tend to reach a point after which they slow down or are not able to accelerate as much as the medalists (**Figures 1**, **3**, **4**, **6**, **8**). In the 800 m event, this difference in trajectory emerges after 600 m and is a similarly critical point for both men and women, although men tend to have a faster start and slower finish (**Figure 2**). With 200 m remaining of the race, it is likely that high force metabolic fuel usage diminishes, and physiological conditioning is at its most discriminating influence (Fukuba and Whipp, 1999; Buchheit and Laursen, 2013). From this point, it appears that the athletes who slow down the least from the fast initial race pace are the most successful at achieving a medal performance. For the shorter distances (800 and 1,500 m), this happens toward the end of the race, characterizing them as more tactical (Renfree et al., 2014) in a head-to-head style of competition where the behavior of opponents plays a larger role. When athletes race in a pack or within each other's proximity for a large part of the race, the final stages have previously been shown to be decisive for winning (Konings et al., 2016a; Noorbergen et al., 2016) in other sports such as short track skating (Konings and Hettinga, 2018b). In our study, the longer IAAF distances such as the 5,000 m, 10,000 m, and 20 km racewalk demonstrate separation points earlier in the race and, particularly for the women, where there is only a small segment of the race where all competitors are together as a pack. This suggests competition outcomes are decided in the earlier stages of the race. In the women's marathon and men's 50 km racewalk, the pace differs between medalists and non-medalists from the start onward, changing the competition in terms of pacing and tactics more into an individual time-trial type events than head-to-head style competition. This inevitably means the dynamics of the competitive and tactical challenges in the race change with the style of event pacing (Konings and Hettinga, 2018d). In addition, it was notable in the marathon that men started slower than women, ran faster in the middle section, but then slowed more than women toward the finish (**Figure 7**). The pacing profiles in these championship marathons differed from those found in world record performances (Díaz et al., 2018, 2019) where pacemakers help the best athletes achieve even or negative pacing and highlights the need for athletes and coaches to appreciate the differences between championship and non-championship racing.

Interestingly, the separation by the medalists from those finishing in lower positions in most races occurs earlier for women than men, indicating that differences in the abilities of women competitors to maintain a high pace throughout the entire race are larger and deviations in pacing occur in the first part of the race. It is also possible the earlier separation of medalists from the racing pack for women could be due to tactical racing factors such as an early realization of being unable to sustain the required speed, or possibly because of greater variation in performance abilities among the runners in the race compared with men. For example, the winning margin between the gold and silver medalist in the 2017 women's 10,000 m was

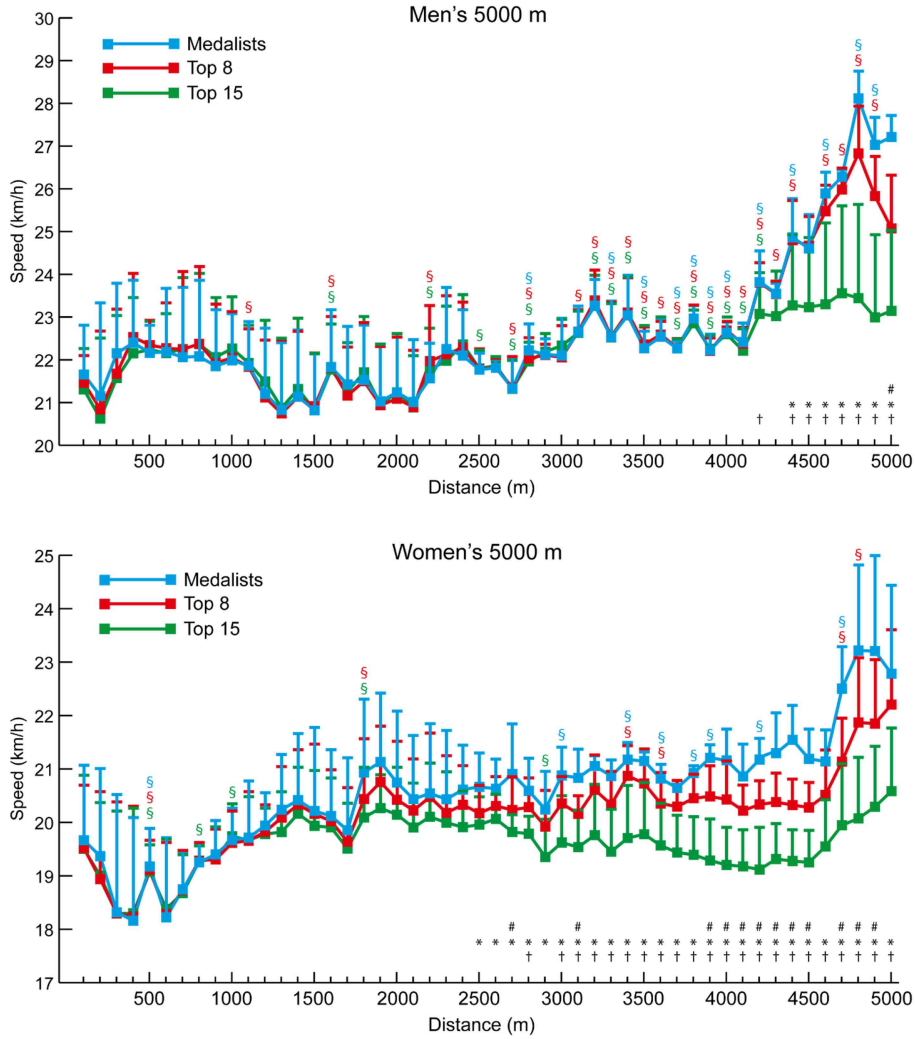

FIGURE 3 | The mean (+ SD) 100-m segment speed for each group of men and women 5,000 m athletes. Differences between successive segments ($p < 0.05$, $d \geq 0.61$) are represented by § (blue for medalists, red for Top 8, and green for Top 15). Differences in segment speed between groups ($p < 0.05$, $d \geq 0.61$) have been annotated for medalists vs. Top 8 (#), medalists vs. Top 15 (*), and Top 8 vs. Top 15 (†).

46 s, whereas it was only 0.43 s in the men's event (IAAF, 2019); indeed, in this men's 10,000 m race the time difference between first and fifteenth athlete was less than the gap between first and second place in the women's race. However, **Tables 1**, **2** do not reveal greater variation among performances between men and women, indicating that our findings provide evidence that there could be greater earlier tactical awareness of appropriate pacing and performance limitations among women, similar to research on sex-based differences in running (Deaner et al., 2015).

The performances evaluated in this study provide useful insights into the strategies employed by finalists in IAAF and Olympic events and their relative success thus far. Men and women share many similar performance attributes and medal success is aligned with the same strategies for each race for both sexes. However, how that dynamically occurs in race pacing is quite different with much different trajectories of how races are managed. The earlier separation between groups for women is a novel finding that indicates some possible lines for future investigation exploring performance among both men and women. This thus results in different competitive and tactical challenges in women's races, that are more similar to individual competition, compared with the men, who run as a pack for longer. The pack running approach of men postpones the decisive stage of the race to the second half of the race in the 5,000 and 10,000 m races and thereby show profiles more similar to the classic head-to-head competition profiles as seen in short track skating (Konings et al., 2016a; Noorbergen et al., 2016). Interestingly, the individual analysis of medalists in the 50 km racewalk, using high-resolution 1-km splits for the first time, highlights these two different approaches. The winner of the men's 50 km adopted a time-trial approach, racing outside the pack and achieving an unprecedented 8-min winning margin. By

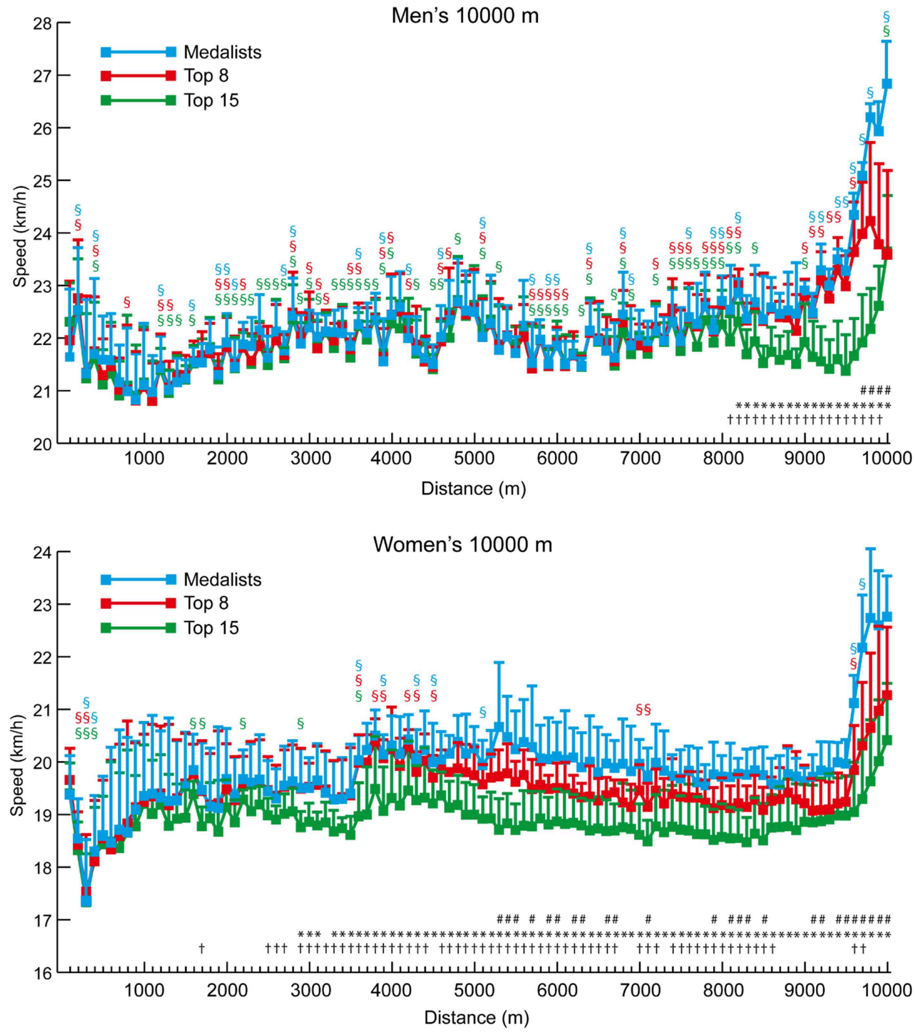

FIGURE 4 | The mean (+ SD) 100-m segment speed for each group of men and women 10,000 m athletes. Differences between successive segments ($p < 0.05$, $d \geq 0.61$) are represented by § (blue for medalists, red for Top 8, and green for Top 15). Differences in segment speed between groups ($p < 0.05$, $d \geq 0.61$) have been annotated for medalists vs. Top 8 (#), medalists vs. Top 15 (*), and Top 8 vs. Top 15 (†).

contrast, the silver and bronze medalists, who were of the same nationality, adopted a pack approach where they raced side-by-side for almost the entire race (**Figure 9**). Adopting packing can be beneficial for performance but does lead to athletes using the exact same pace set by others, regardless of their personal optimal strategy (Hanley, 2015), and in the women's 50 km, the silver medalist could not stay in a pack with the leader. Athletes should note that different pacing profiles can arise in competition, especially over the longer distance races, and prepare for each eventuality in training.

It is evident that in the 800 m event, a positive pacing strategy was dominant for all groups of men and women, whereby the athletes ran the second lap slower than the first (**Table 3**), confirming pacing profiles identified previously for all rounds of 800 m championship racing (Hanley et al., 2019). The staggered start used in 800 m, which makes it unique amongst distance races, is a likely factor in this fast start given the athletes need to reach the 200-m distance in a strong tactical position, and do not have nearby opponents as pacing guides (Casado and Renfree, 2018; Hanley et al., 2019). It is not an unusual scenario whereby an 800 m runner performs poorly in a major championship, well below their season's best performance (Hanley et al., 2019), and this performance discrepancy can arise because the athlete has prepared for the championships by taking part in fast, structured races with pre-planned pacemakers. These non-championship races, such as those in the IAAF Diamond League, typically present a much more even paced profile (Filipas et al., 2018) than championship races, and middle-distance coaches should study carefully the actual pacing profiles that occur in 800 m championship racing and prepare their athletes accordingly. Beyond this race distance, the successful (i.e., medalist) strategy switches to a negative pacing profile, where speed is faster

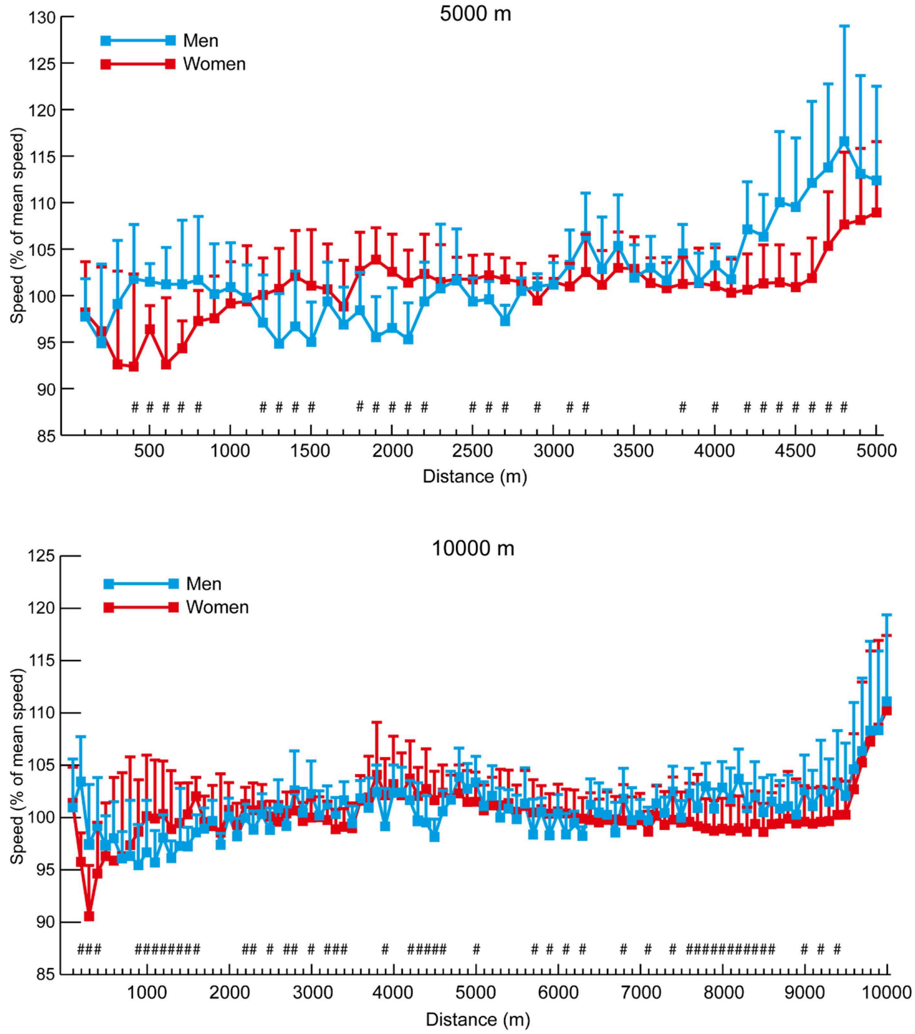

FIGURE 5 | The mean (+ SD) section speed expressed as a percentage of mean speed for all men and women in the 5,000 and 10,000 m events. Differences in segment speed percentage between men and women ($p < 0.05$, $d \geq 0.61$) have been annotated (#).

in the second half of the race. Indeed, for medalists, the strategic commonality is a wholly negative pacing profile for all distances beyond 800 m for all groups of men and women medalists (**Table 3**). Groups of athletes performing slower than the medalists (e.g., Top 8 and Top 12/15) show greater variation in pacing strategies with some adopting positive pacing profiles whereby pace declined in the second half of the race in contrast to the highest performing athletes. Nevertheless, medalist success in all events was consistently achieved with a negative pacing strategy for men and women in events beyond 800 m. There are several possible causes for a negative pacing strategy in distance events, but most likely it reflects the small margins of difference in performance times between athletes (**Table 1**) competing in head-to-head competition, and the necessity when racing to finish an event strongly to win among equally motivated and similarly capable opponents. The impact of opponents has recently been explored in research that clearly demonstrates that racing poses a tactical challenge to all competitors (Konings and Hettinga, 2018b), and in athletics it has been demonstrated that some retention of physical reserve is important to be able to respond to the strategies of opponents (Mytton et al., 2015).

In the longer events, a similar pattern emerges for all distances, although, as these are performed with a negative pacing strategy, pace becomes faster in some cases. Rather than slowing down the least being most important (as in the 800 m), the medalists emerge on a different pacing trajectory. It is interesting that the crucial point of separation in pacing trajectory occurs at a much earlier stage of races for women than men in events longer than 800 m. For example, in the 1,500 m (**Figure 1**), male medalists separated from the slowest runners (those finishing 9th–12th) and the Top 8 athletes in the last 100 m. This same effect can be seen for women at 1,200 m for the Top 12 athletes and 1,300 m for the Top 8. Similarly, over 5,000 m, male medalists separated from the slowest pack members later (84% of race

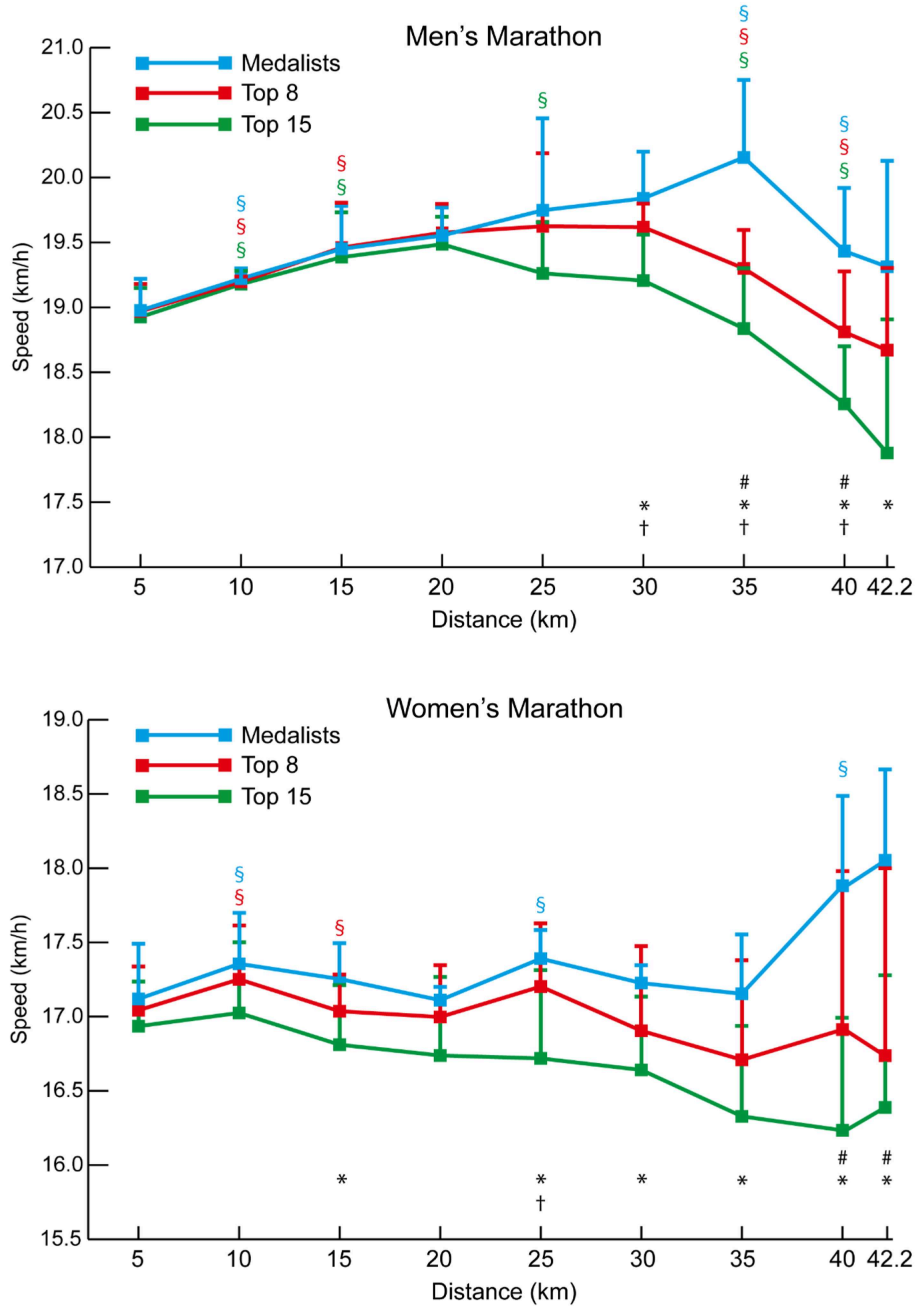

FIGURE 6 | The mean (+ SD) 5-km and final 2.2-km segment speeds for each group of men and women marathon athletes. Differences between successive segments ($p < 0.05$, $d \geq 0.61$) are represented by § (blue for medalists, red for Top 8, and green for Top 15). Differences in segment speed between groups ($p < 0.05$, $d \geq 0.61$) have been annotated for medalists vs. Top 8 (#), medalists vs. Top 15 (*), and Top 8 vs. Top 15 (†).

distance: 4,200 m) than for women, for whom this occurred at 50% of race distance (2,500 m). Clear trajectories emerge for those finishing as medalists vs. middle-ranked non-medalists and the slower remaining athletes. In the 10,000 m race, the effect is very pronounced (**Figure 4**) with men remaining as a tighter group up to 80% of distance where the slower athletes are dropped from the pack, and the Top 8 athletes are only dropped at 96% of total distance. For women, the slowest pack begin to run slower at only 17% of race distance, with the Top 8 being dropped at 53% of race distance. Such profiles and patterns can be seen across all events up to and including the 50 km racewalk. It should be noted, however, that in many events the medalists did not run faster than lower-finishing athletes in every split after a certain distance, and thus these small bursts of speed gradually

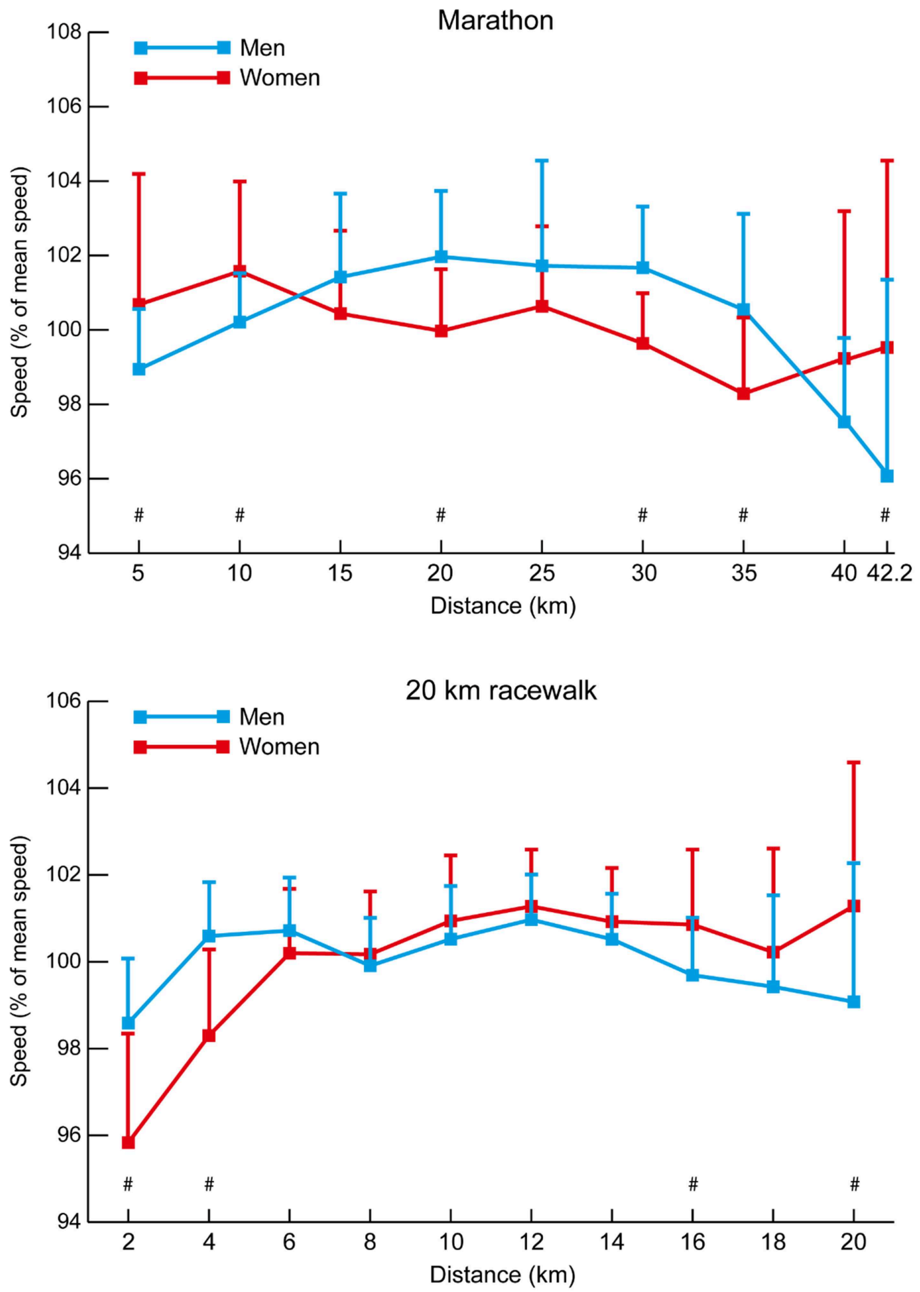

FIGURE 7 | The mean (+ SD) section speed expressed as a percentage of mean speed for all men and women in the marathon and 20 km racewalk events. Differences in segment speed percentage between men and women ($p < 0.05$, $d \geq 0.61$) have been annotated (#).

separated the best athletes from the others until the gap between them was too large to overcome (Fukuba and Whipp, 1999). Like the fast start over the first 200 m in the 800 m, the lack of a difference in split speeds can be due to tactical approaches, such as only overtaking on the straight 100-m sections (Aragón et al., 2015). A key point shown by the current study is that in championship racing, an even pace is not necessarily a winning pace; the ability to keep energy in reserve for a fast endspurt or smaller, but sustained bursts throughout the race is important for separating from lower-placed finishers and might be developed by the high proportion of tempo running and short interval training sessions adopted by world-class distance runners and are thus recommended to coaches (Casado et al., 2019).

Decreases in running speed are not always directly related to metabolic fatigue (Renfree and St Clair Gibson, 2013); other reasons for disparities in pacing strategy between the successful negative pacing strategy employed by medalists and positive pacing (i.e., slower in the second half of a race) by lower

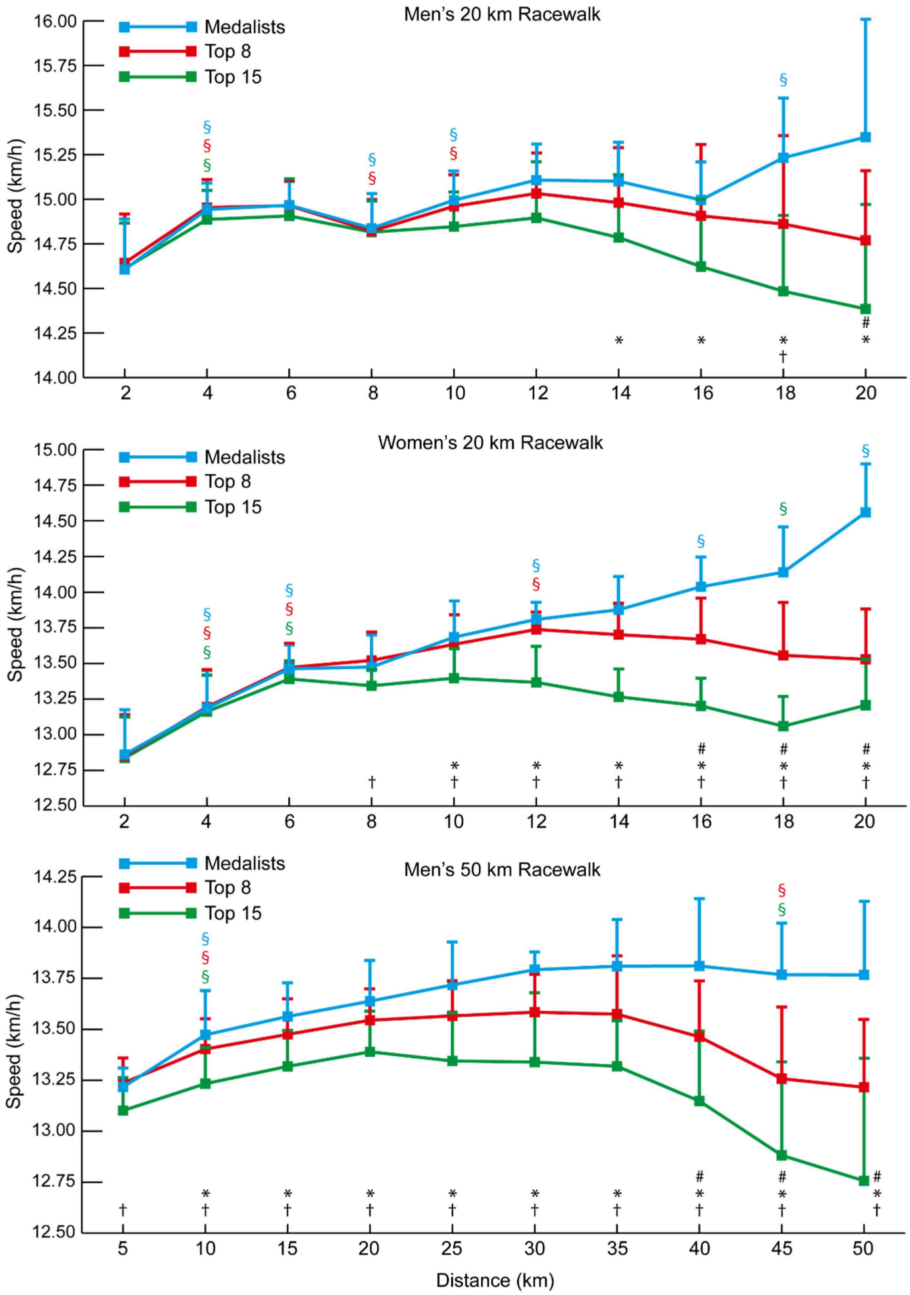

FIGURE 8 | The mean (+ SD) 2-km segment speed (20 km event) and 5-km segment speed (50 km event) for each group of men and women racewalkers. Differences between successive segments ($p < 0.05$, $d \geq 0.61$) are represented by § (blue for medalists, red for Top 8, and green for Top 15). Differences in segment speed between groups ($p < 0.05$, $d \geq 0.61$) have been annotated for medalists vs. Top 8 (#), medalists vs. Top 15 (*), and Top 8 vs. Top 15 (†).

performing athletes could be a psychological acceptance of the inevitability of race outcome by the non-medalists. It is plausible that once an approximate order of supremacy has been established in a race, lower performing athletes who are not in contention for a medal accept the race outcome to some extent, retain some energy and do not increase their pace to that commensurate with maximal effort. This tactic can be adopted by lower-finishing athletes to avoid a "catastrophic event" (Thiel et al., 2012), whereby the athlete would run so fast relative to ability in trying to keep up with the leaders that they would have to drop out. In events such as rowing, it is common to see differential pacing strategies according to ability in a race, where race outcome is often established as early as 25% of the total distance (Edwards et al., 2016) and ~50% of distance in Olympic events (Garland, 2005). However, it should not be forgotten that many athletes are likely to be realistic about their prospects

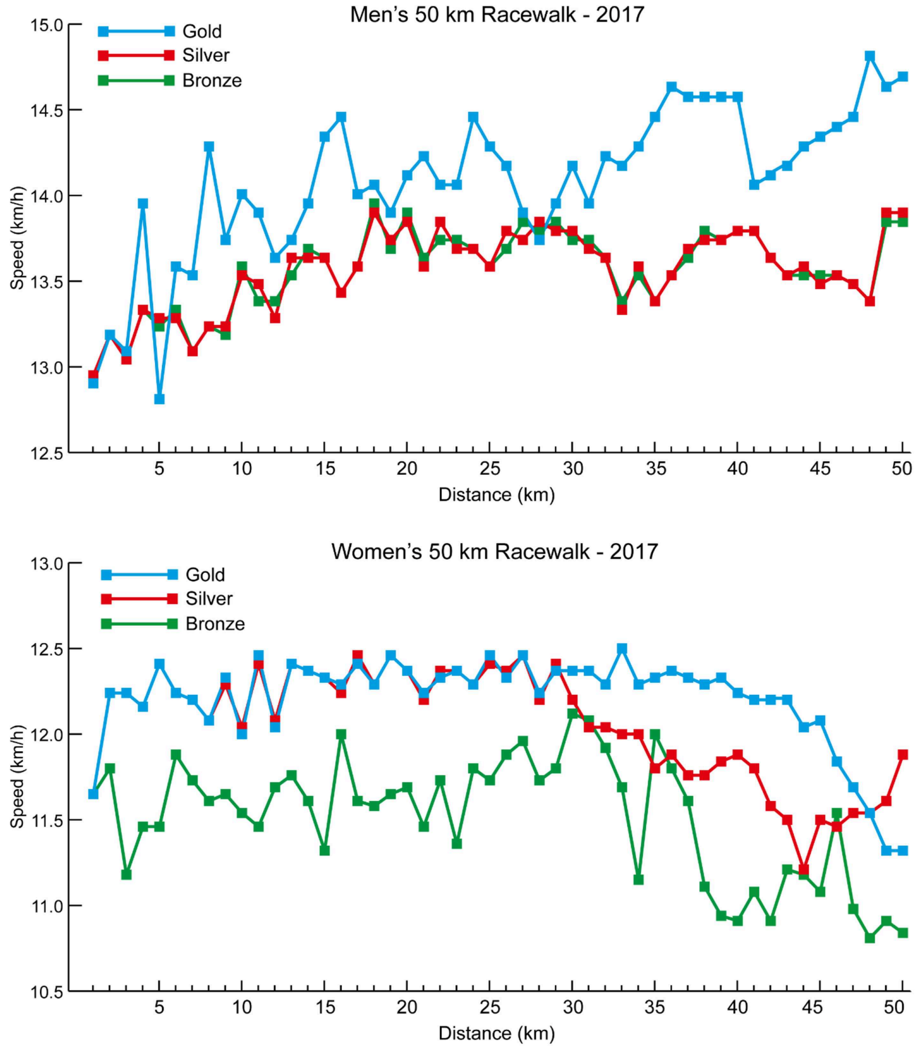

FIGURE 9 | The individual 1-km segment speeds for the medalists in the men's and women's 50 km racewalk events at the 2017 IAAF World Championships.

in global finals and set goals relative to their ability: setting a personal best time, making the final, or finishing in the top 8 or top 15 can be important for an individual athlete, especially as finishing in these positions can be linked to future governing body funding (e.g., Athletics Ireland, 2019), and success is a relative term.

It is possible that our findings simply provide evidence that lower performing athletes in races adopt an overly optimistic initial race pace to match the pace of the eventual medalists for as long as they can, and the consequence of this is to experience progressively greater accumulation of fatigue and a slowing of pace over the race distance compared with that of medalists (Renfree and St Clair Gibson, 2013). This tactic of following the leader is the least psychologically taxing strategy given the lack of conscious pace judgment but can mislead less able athletes into adopting an unsustainable pace (Renfree et al., 2015; Hanley, 2018). The metabolic cost of sustaining a common fixed running speed is less physically demanding for the highest performance athletes than slower athletes because the intensity is at a lower percentage of their maximum capabilities (Filipas et al., 2019). As such, it is not surprising that lower performing athletes have less available energy later in a race to adopt the same racing strategy as the medalists. Certainly, in comparison with a time trial, a race is characterized by attempting to beat the opposition rather than focusing purely on performance time, and other competitors influence the process of decision-making regarding how and when to invest energy over a race (Konings et al., 2016b; Konings and Hettinga, 2018a). This can lead to dynamic and tactical pacing in a race situation to which athletes are unaccustomed, and which is thought to increase the physical challenge of exercise compared with self-paced exercise (Lander et al., 2009). This can manifest as misjudgment of initial race pace among the lower performing athletes or a willingness to match the pace of the medalists where the consequences are eventually being unable or unwilling to sustain a higher than usual pace, and thereafter suffering the consequences of fatigue and diminishing pace. Once the slower athletes realize they can no longer proceed at the same pace as the faster athletes, separation from the racing pack occurs and acceptance can set in thus lowering their pace further, adding to the performance costs of having already run the race to this stage at a speed faster than they might have otherwise planned. It has been shown that dependency of the opponent impacts on decision-making, so when athletes are dependent of the other athlete to win, this changes competition dynamics. A higher interdependency between athlete and opponent alters in-race adaptations based on the opponent's behavior (Konings et al., 2019). In the context of exercise regulation, attentional cues such as the proximity of the opponent are likely to be used in an adaptive way according to their availability and situational relevance, consistent with a decision-making framework based on the interdependence of perception and action. However, this raises the question of whether non-medalists might perform better if they ignored the pace of runners showing faster initial pace in the race if it leads to misjudgment in their own performance and premature fatigue. They might simply do better to complete their own race strategy in isolation, and adopt an even pace, as occurs in non-championship races (Filipas et al., 2018). Yet, it might also be that winning chances are only present when in the leading group, so even though deciding to race one's own pace could lead to better performance, athletes might not want to give up their chance to win, particularly in highly competitive sports environments (Casado and Renfree, 2018; Hanley and Hettinga, 2018) with marathon runners, for example, being prepared to risk a potentially harmful fast start if it presents them with the chance of success (Deaner et al., 2019). The impact of high motivation and passion for sports has previously been linked to athletic decision-making within a race but also throughout a season (Schiphof-Godart and Hettinga, 2017) and is expected to be particularly relevant in high-standard head-to-head events such as the IAAF World Championships.

The performance implications of pacing in the heat such as in the 2019 IAAF World Championships in Doha or Olympic Games in Tokyo could require considerable adjustment in pacing strategy. Exercise in the heat poses severe challenges that mean either the same strategic approach to racing or the adoption of a different strategy. Heat often proves a decisive factor in performance outcome, particularly in endurance events (Guy et al., 2015). For example, an earlier study of race outcomes in IAAF World Championships (1999–2011) (Guy et al., 2015) demonstrated that in hot environments ($>25^{\circ}$C), endurance performances were worse ($\sim$3% reduction in performance, Cohen's $d = 0.8$; large impairment), compared with cooler conditions ($<25^{\circ}$C). By contrast, performance in short duration sprint events was augmented in the heat compared with temperate conditions ($\sim$1% improvement, Cohen's $d = 0.8$; large performance gain). Consequently, understanding the demands of the race, the opposition and the environmental challenges of racing in the heat will all be crucial to success. The heat effects of Doha's climate are most likely to affect the road races (marathon and racewalks) (Ely et al., 2008) as these will be held outside the air-conditioned stadium. To account for the likely hot conditions, the road races will be held at nighttime (approximately midnight) and this in itself could present challenges for athletes more accustomed to competing in the early morning or evening. Although it is possible, it seems unlikely that negative pacing in endurance events would not be adopted in the heat given its consistent success, and therefore a within-style slowing of pace adjustment is probably to cope with the environmental and course conditions (Angus, 2014). Nevertheless, further high frequency analysis of elite performance pacing in the heat would be a meaningful contribution to the literature when sufficient data become available.

Analysis of such comprehensive data as explored in the present study provides an opportunity to investigate tactics and race strategies pertinent to current race performances for those men and women currently competing in world-class distance events, providing meaningful insights for upcoming events. Indeed, the results found provide an invaluable guide for coaches to prepare their athletes for the likely pacing profiles adopted in each of these events, even though a limitation of the current study design is that analyses are purely descriptive and have not taken place under controlled circumstances, which means that findings and potential extrapolations to other races need to be interpreted with care. Confounding factors could be, for example, differences in climates, altitude and timing of the events. However, at the same time, our descriptive analysis of in-race data of world-class athletes is highly ecologically valid, and relies on a very large database with high resolution performance analysis, which is a strength of the current approach and could provide meaningful and unique insights into world-class competition. In analyzing the world's best athletes, it was also inevitable that particularly successful athletes were analyzed in more than one competition. On the one hand, this means that caution must be taken when interpreting the statistical results, but on the other it does allow for an appreciation of how contemporary successful athletes pace their races.

CONCLUSIONS

This is the first study to demonstrate a comprehensive separation effect for pacing by medalling athletes and their opponents across the full range of middle-distance, long-distance and racewalk events for men and women. This effect seems consistent for men and women, although it occurs at an earlier stage of most race distances for women. However, it is also evident in events such as the marathon and racewalks, particularly among women, that the pacing trajectories of medalists vs. other athletes can take completely different paths from the start of the race, indicating the specific impact of opponents on each race distance is likely to be different across race distances. As such, some races might be less about direct impacts of head-to-head competition than being more akin to contested time-trial performances. It is also evident that, in events longer than 800 m, the commonly successful racing strategy is to complete the first half of the race at a slower pace than the second half (negative pacing). This demonstrates the importance of the ability to change speed and respond dynamically to changes in pace in endurance events although the dominant characteristic of long-distance athletes is endurance capability.

DATA AVAILABILITY

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

BH conducted data analysis and graphical representation of the findings. All authors contributed to conception and design of the work, drafted it, and revised it critically for important intellectual content, approved the final version of the manuscript, agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

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Assessment of IAAF Racewalk Judges' Ability to Detect Legal and Non-legal Technique

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IAAF Rule 230.2 states that racewalkers must have no visible (to the human eye) loss of contact with the ground and that their advancing leg must be straightened from first contact with the ground until the "vertical upright position." The aims of this study were first to analyze racewalking judges' accuracy in assessing technique and, second, to measure flight times across a range of speeds to establish when athletes were likely to lose visible contact. Twenty racewalkers were recorded in a laboratory using a panning video camera (50 Hz), a high-speed camera (100 Hz), and three force plates (1,000 Hz). Eighty-three judges of different IAAF Levels (and none) viewed the panned videos online and indicated whether each athlete was racewalking legally. Flight times shorter than 0.033 s were detected by fewer than 12.5% of judges, and thus indicated non-visible loss of contact. Flight times between 0.040 and 0.045 s were usually detected by no more than three out of eight judges. Very long flight times (≥0.060 s) were detected by nearly all judges. The results also showed that what judges generally considered straightened knees (>177°) was close to a geometrically straight line. Within this inexact definition, IAAF World Championship-standard Level III judges were most accurate, being more likely to detect anatomically bent knees and less likely to indicate bent knees when they did not occur. For the second part, the men racewalked down a 45-m indoor track at 11, 12, 13, 14, and 15 km/h in a randomized order, whereas the women's trials were at 10, 11, 12, 13, and 14 km/h. Flight times, measured using an OptoJump Next photocell system (1,000 Hz), increased for the men from 0.015 s at 11 km/h to 0.040 s at 14 km/h and 0.044 s at 15 km/h, and for the women from 0.013 s at 10 km/h to 0.041 s at 13 km/h and 0.050 s at 14 km/h. For judging by the human eye, the threshold for avoiding visible loss of contact therefore occurred for most athletes at ∼14 km/h for men and 13 km/h for women.

Keywords: athletics, biomechanics, force plate, testing, videography

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INTRODUCTION

Racewalking is part of the athletics program at the Olympic Games, International Association of Athletics Federations (IAAF) World Championships, and all other major athletics events. Competitions are held over 20 km for men and women, with a 50 km event for women first added in 2017 to join the longstanding men's 50 km event. IAAF Rule 230.2 states that racewalking is a progression of steps with no visible (to the human eye) loss of contact with the ground and that the athlete's advancing leg must be straightened from first contact with the ground until the vertical upright position (IAAF, 2017). The "vertical upright position" was a term introduced by the IAAF more than 45 years ago, and is effectively the moment when the athlete's torso passes over the foot (IAAF, 1972). To ensure athletes are complying with Rule 230.2, qualified judges are positioned on the course to scrutinize the racewalking techniques used. If a judge observes an athlete exhibiting loss of contact or a bent knee, a red card is sent to the Chief Judge (IAAF, 2017). Three red cards from three different judges lead to disqualification (in international competition, the three judges must represent different nations), or in some events, the athlete suffers a time penalty (IAAF, 2017). Before issuing a red card, if a judge is not completely satisfied that a racewalker is complying with the rule, the athlete is shown a yellow paddle indicating the offense. Judges at major global championships, such as the Olympic Games, are selected from the IAAF's panel of Level III judges, who must perform well in written, verbal and video-based examinations. Judges at Area competitions (e.g., the European Championships) must be on at least the IAAF Level II panel, which also requires the passing of examinations. National competitions can be judged by individuals with IAAF Level I qualifications, which many nations incorporate into their own judge education programs.

It is important to note from IAAF Rule 230.2 that judging accuracy in identifying visible loss of contact and bent knees is equally important. As a result, paying attention to both aspects of the rule is crucial for athletes and coaches, as infringing either part can lead to disqualification: across all four 20 and 50 km races at the 2017 IAAF World Championships, seven athletes were disqualified for three red cards for loss of contact, six for three red cards for bent knees, and six for a mixture of contact and knee infringements (IAAF, 2019). Overall, 91 red cards were awarded for loss of contact (mostly in the 20 km races), and 57 for bent knees (mostly in the 50 km races). Although there have been many studies on the biomechanics of racewalking, very little research on judging itself has been conducted. Two studies from the early 1990s included experiments that found the judges assessed were typically unable to observe loss of contact when it lasted <0.04 s. However, there were very few judges assessed: the first study (Knicker and Loch, 1990) featured one international judge and two national judges, whereas the other used "a coach of long-standing international experience" (De Angelis and Menchinelli, 1992, p. 87). These studies were conducted before the current racewalking rule was introduced in 1995, and at the time meant that athletes did not have to have a straightened knee by first contact, only at the instant of the vertical upright position. New research is therefore warranted that reflects modern racewalking techniques and more up-to-date judging practices.

A key point to reiterate is that there are no current set definitions of legal loss of contact or bent knee angles, except that they are judged with the human eye by appointed judges. With the aid of video cameras, previous research has found flight times as high as 0.07 s (Knicker and Loch, 1990), although more modest mean values of ∼0.03 s have been found in recent competition and laboratory studies (Hanley et al., 2014; Hanley and Bissas, 2017), below the 0.04 s threshold suggested by Knicker and Loch (1990) and De Angelis and Menchinelli (1992). Nevertheless, the mean flight time of 0.03 s contributed to a mean flight distance of 0.12 m per step, and longer flight distances were found to correlate with racewalking speed (Hanley and Bissas, 2016), showing that it is important for judges to be consistent with their decisions to avoid individual athletes gaining an advantage. With regard to knee angles, Cairns et al. (1986) defined knee straightness as 175° and angles beyond that as hyperextension. Similarly, Knicker and Loch (1990) defined straightness as between 175 and 185°, but these values should not apply to current racewalkers given those studies were conducted under the pre-1995 rule. In terms of the actual angles that occur, the results of a very recent laboratory study showed that the mean knee angle at first contact was 180° (Hanley et al., 2018), similar to that found in world-class competition (Hanley et al., 2014), in laboratory settings using high-speed cameras (Padulo et al., 2013), and using optoelectronic systems (Pavei and La Torre, 2016), but whether this matches judges' opinions has not been hitherto analyzed. Furthermore, it has not been established whether there are differences in accuracy between IAAF judging Levels, a potentially important factor in deciding the future direction of judge education.

Racewalking is a very technical event with its own unique gait pattern, determined by IAAF Rule 230.2 and the athlete's attempts to maximize speed and efficiency. Judging the racewalk event accurately is a difficult skill and subjective by its very nature, so it will therefore be very beneficial to conduct new research on this topic with a far greater number of judges than those of previous two studies (Knicker and Loch, 1990; De Angelis and Menchinelli, 1992), particularly now that an examination must be passed to join the judging pool, and because of the post-1995 change in definition of the governing rule. Recent advances in technology, including internet-based surveys and digital videography, mean that reaching a greater number of judges worldwide is now possible. Similarly, because it has been proposed that electronic chip insole technology should be incorporated into racewalking competitions from 2021 (IAAF, 2019) for the measurement of loss of contact, establishing how much flight time must occur for visible detection, and at what speeds these typically occur (or not), is timely. For coaches, knowing what other spatiotemporal values, such as those of step length and step frequency, are likely to occur at speeds when loss of contact is visible is useful in monitoring athletes' technique. Furthermore, unlike loss of contact, no attempt has been made previously to establish a "threshold" for bent knees, which would assist with coach, athlete and judge education. The aims of this study were first to analyze racewalking judges' accuracy in assessing technique and, second, to measure flight times across a range of speeds to establish, based on the judges' accuracy scores, at what speeds athletes were likely to begin to lose visible contact.

MATERIALS AND METHODS

Research Approval

All human subjects were treated in accordance with established ethical standards. The protocol was approved by the Carnegie School of Sport Research Ethics Committee. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The subjects were provided with Participant Information Sheets, and in accordance with the Carnegie School of Sport Research Ethics Committee's policies for use of human subjects in research, all subjects were informed of the benefits and possible risks associated with participation and informed of their right to withdraw at any time.

Part 1: Data Collection and Analysis of Athletes for Judging Study

Participants

Twenty-six athletes from 12 nations participated in this part of the study. Of the 26, six athletes' videos were used for practice data in the following part of the study and excluded from all analyses. Of the remaining 20 athletes, nine were men (age: 23 ± 5 years, height: 1.76 ± 0.04 m, mass: 63.9 ± 5.1 kg, 20 km personal record (PR): 1:26:07 ± 6:37), and 11 were women (age: 26 ± 6 years, height: 1.68 ± 0.08 m, mass: 57.9 ± 10.3 kg, 20 km PR: 1:33:35 ± 6:19). One of the men was an U20 (junior) athlete who had not yet competed over 20 km. Ten of the 20 athletes had competed at the 2016 Olympic Games or 2017 IAAF World Championships.

Data Collection

Before testing, the athletes were given time to warm up and prepare, with practice trials taken to become accustomed to the laboratory setting. The participants racewalked along a 45-m indoor running track in the biomechanics laboratory on multiple occasions. The testing area was kept clear of equipment, and the floor cleared of any tape or markings. They were filmed using a Sony HXR-NX3 digital HD camcorder (50 Hz); the settings chosen were based on those recommended for upload to YouTube (1080/50p, progressive scanning, 1920 × 1080 px), which housed the videos (although they were accessed by judges in the second part of the study via online survey software and were not directly accessible on YouTube). The camcorder recordings were achieved using a panning technique, and the athletes racewalked both left-to-right and right-to-left. The video capture area was flooded with light from 26 overhead lights (∼104 kW) that allowed very high-quality pictures to be obtained (the shutter speed selected was 1/1,750 s). The athletes were asked to racewalk at a variety of paces, completing at least six trials each, with the trial best suited to analysis chosen based on accuracy of contact with the force plates, quality of camera footage, and symmetry between left and right contact times (Tucker and Hanley, 2017).

High-speed video data were recorded simultaneously with the panning footage using a stationary camera (Fastec TS3, San Diego, CA). The resolution of the camera was 1280 × 1024 px, a 25 mm lens was used, the shutter speed was 1/2,000 s and the f-stop was 2.0. This camera was positioned ∼10 m from and perpendicular to the plane of racewalking, and recorded movement over a distance of 5 m around the data capture area to allow for the calculation of knee angles. Four 3 m high reference poles were placed in the center of the camera's field of view in the center of the running track in the sagittal plane. The reference poles provided 12 reference points (up to a height of 2 m) that were later used for calibration (scaling) when calculating knee angles.

In the area where the high-speed camera was focused, the athletes racewalked across three adjacent force plates (9287BA, Kistler Instruments Ltd., Winterthur), from which any loss of contact time was measured (simultaneously with the cameras). These force plates (1,000 Hz) were 900 mm long and 600 mm wide (natural frequency ≈ 750 Hz (x-, y-), ≈520 Hz (z-); linearity < ±0.5% full scale output (FSO); cross talk < ±1.5%; hysteresis < 0.5% FSO) and placed in a customized housing in the center of the track. The force plates were covered with a synthetic athletic surface so that the force plate area was flush with the rest of the runway to preserve ecological validity (Bezodis et al., 2008), while still being separate from the surrounding surface.

Data Analysis

The video files were digitized manually (SIMI Motion 9.2.2, Munich) by a single experienced operator. Digitizing was started at least 15 frames before first contact (heel-strike) and completed at least 15 frames after toe-off to provide padding during filtering (Smith, 1989). Each video was first digitized frame by frame, and adjustments made as necessary using the points over frame method (Bahamonde and Stevens, 2006). The segment endpoints used to calculate the knee angle were the hip joint, knee joint, and ankle joint. A recursive second-order, low-pass Butterworth digital filter (zero phase-lag) was used to filter the raw knee angle data (Winter, 2005). The cut-off frequencies were calculated using residual analysis (Winter, 2005). The knee angle was calculated as the sagittal plane angle between the thigh and lower leg segments, and rounded to the nearest integer. Knee angles were considered to be 180° in the anatomical standing position, and angles beyond this as hyperextension. The knee angle has been presented in this study at specific events of the gait cycle as defined below:

- First contact—this was the first visible point during stance where the athlete's foot clearly contacts the ground (heel-strike).
- Midstance—this was a visually chosen position where the athlete's foot was directly below the hip, used to determine the "vertical upright position."

The force data were smoothed using a recursive second-order, low-pass Butterworth filter (zero phase-lag) at 50 Hz (Hanley and Bissas, 2017). The mean and standard deviation (SD) of the noise occurring during the final 50 ms before ground contact (visual inspection) were calculated, and first contact was considered to begin when the vertical force magnitude was greater than the mean plus 3SD of the noise (Addison and Lieberman, 2015; Hanley and Tucker, 2019). The mean and 3SD of the noise during the first 50 ms after toe-off were used in a similar way to identify the end of contact and the beginning of flight (i.e., loss of contact). Flight time was defined as the time duration from toe-off of one foot to the first contact of the contralateral foot (Padulo et al., 2014).

Part 2: Data Collection and Analysis of Judges

As previously described, 20 of the 26 athletes' videos were chosen to be part of the online judging test. Of the other six, five were chosen as "practice trials," and one was chosen as a trial to allow participants to adjust their computer settings. Thirteen of the videos were of athletes racewalking from left-to-right, and seven from right-to-left. An online survey system, Qualtrics, was used to collect responses from judges.

The vid Tube to prevent access from unauthorized viewers. The following code was used to control how the videos played within Qualtrics (the YouTube playlist title beginning "xyz" in the example given below is fictitious):

- <iframe width="960" height="540" src="https://www.youtube.com/embed/xyz123456?autoplay=1&&loop=1&playlist=xyz123456;&rel=0&showinfo=0&modestbranding=1&controls=0" width="960" wmode="transparent"> frameborder="0" allowfullscreen></iframe> Please choose one of the following:

where:

- autoplay = 1—meant the video began automatically
- loop = 1—replayed the video on a continuous loop until the participant had answered the question and moved to the next video
- rel = 0—prevented related videos from appearing via YouTube at the end of each clip
- showinfo = 0—prevented the participant from viewing the video file details
- modestbranding = 1—restricted the amount of time the YouTube logo was visible on screen
- controls = 0—removed the option for participants to pause, play or slow the video

In addition, the code below created a transparent mask over each video so that participants could not click on it (which could have been used to pause it):

- <div style ="position: absolute;top:0px;left:0px;width: 1000px;height:570px;background-color: white;z-index:2;opacity:0.0;filter: alpha(opacity = 0)"></div>

Respondents were asked to watch the 20 videos in turn and to make a judging decision based on what they saw for each one. The symbols used in the survey for infringements reflected those used in competition: $\sim$for loss of contact and $>$ for bent knees.

We disseminated the survey directly from Qualtrics, via social media and via email. Email details for IAAF Level II and Level III judges were obtained from the IAAF, and access to the survey could be accessed by the email recipient only. Before beginning the survey, participants were provided with an online Participant Information Sheet and Informed Consent Form; all participants had to declare that they were at least 18 years old. Apart from responses to the actual racewalking videos, we used the Qualtrics system to request the following information from participants:

- Sex and age (one selection allowed): (male; female)/(18–29; 30–39; 40–49; 50–59; 60–69; 70+)
- IAAF Area of residence (one selection allowed): (Africa; Asia; Europe; North America; Oceania; South America)
- Involvement in racewalking (multiple selections allowed): (judge; administrator/governing body official; athlete; coach; supporter/fan; scientist/researcher; none)
- Judging qualifications (one selection allowed): (IAAF Level III; IAAF Level II; IAAF Level I; National qualification; none)
- Highest standard of competition judged at (one selection allowed): (World Championships/Olympic Games; Area competition; World age-group championships; Area age-group championships; International match/Regional championships; Local/regional championships; national championships; none).

The Qualtrics software also recorded data of total time spent on the survey per respondent and time spent per individual video. There was a total of 223 responses to the survey; of these, 121 were incomplete responses (in some cases, we were contacted directly by judges to say that they had begun the survey but then realized their YouTube settings were less than optimal, and began the survey again on another computer). Respondents were asked about their quality setting when using YouTube (as stated above, a non-assessed video was provided for respondents to alter their settings to the best quality available, with this setting automatically retained for the test videos). Because it would have led to unsuitably low video quality for judging, 17 respondents who stated that their resolution was lower than 480p were excluded from the final survey.

After excluding those who had inappropriate quality settings, 63 men and 22 women were included in the final sample; their Area and qualifications are shown in **Table 1**. As very few judges ($N = 4$) described themselves as being IAAF Level I, their responses include those who described themselves as having national qualifications. Responses from those who had no qualifications, where respondents could choose more than one option to describe their involvement in racewalking, showed that the largest subgroup were athletes ($N = 15$), with fewer describing themselves as either coaches ($N = 8$), racewalking supporters/fans ($N = 7$), scientists/researchers ($N = 3$), or administrators/governing body officials ($N = 1$). With regard to age groupings, five respondents were in the 18–29 category, 13 were in the 30–39 category, 19 were in the 40–49 category, 24 were in the 50–59 category, 17 were in the 60–69 category, and seven were 70 years old or older.

Part 3: Changes in Spatiotemporal Variables With Increased Speed

Twenty athletes participated in this part of the study, of whom 14 had also taken part in the judging video study. Eleven of these racewalkers were men (age: 26 ± 4 years, height: 1.77 ± 0.06 m, mass: 64.4 ± 4.7 kg, 20 km PR: 1:23:02 ± 2:28) and nine were women (age: 25 ± 4 years, height: 1.68 ± 0.09 m, mass: 57.5 ± 10.6 kg, 20 km PR: 1:32:23 ± 6:02). Fifteen of these athletes had competed at the 2016 Olympic Games or 2017 World Championships.

TABLE 1 | Number of judges from each area at each level.

Area	Level III	Level II	Level I	No qualification	Total
Africa	0	0	3	1	4
Asia	1	1	3	0	5
Europe	10	8	15	14	47
North America	2	5	5	6	18
Oceania	0	1	6	1	8
South America	0	2	1	0	3
Total	13	17	33	22	85

The men racewalked multiple times down the same 45-m indoor track as in the earlier part of the study at 11, 12, 13, 14, and 15 km/h in a randomized order, whereas the women's trials were at 10, 11, 12, 13, and 14 km/h. The time taken to cover the analyzed 5 m distance in the data capture area was measured using dual photocell Witty timing gates (Microgate, Bolzano, Italy), and had to be within 3% of the target time to be included for analysis. Flight times were measured for each trial at 1,000 Hz using five connected 1 m strips of an OptoJump Next system (Microgate, Bolzano, Italy). Results from the OptoJump Next system were extracted using specific settings (GaitIn_GaitOut) of 2_2 based on the number of light emitting diodes (LEDs) that formed the baseline and found to be optimal during a reliability study (Hanley and Tucker, 2019). The minimum threshold for flight time was set at 0.001 s (Hanley and Tucker, 2019). The variables extracted for this part of the study were step length, step frequency, contact time, and flight time.

Statistics

All statistical analyses were conducted using SPSS Statistics 24 (IBM SPSS, Inc., Chicago, IL). Results are presented as means and SD. Pearson's product moment correlation coefficient (r) and regression analysis were used to find associations between judges' response rates and flight times and knee angles; an alpha level of 5% was set. Effect sizes for correlations were either small (r = 0.10–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), or extremely large (>0.90) (Hopkins et al., 2009). For the regression analysis, a component had to be statistically significant at the 0.05 level and account for at least 3% of the variance in detection rate score to be retained in the final model, whereby a polynomial regression analysis was employed to fit the data with an appropriate quadratic model. Coefficient of determination (R^2) has been reported for the regressions (Field, 2009). Independent t-tests were conducted to compare values between men and women where appropriate, with adjustments made when Levene's test for equality of variances was <0.05 (Field, 2009). Effect sizes for differences between groups were calculated using Cohen's d (Cohen, 1988), rounded to two decimal places and considered to be either trivial ($d \leq 0.20$), small (0.21–0.60), moderate (0.61–1.20), large (1.21–2.00), or very large (≥2.01) (Hopkins et al., 2009). On the occasions where Cohen's d was calculated, only those results where the effect sizes were moderate, large, or very large have been included. One-way repeated measures analysis of variance (ANOVA) was conducted at five speeds with repeated contrast tests conducted to identify changes between successive measurement speeds (Field, 2009). An alpha level of 5% was set for these tests with Greenhouse-Geisser correction used when Mauchly's test for sphericity was significant.

RESULTS

The results presented below first comprise the judging decisions made via Qualtrics with regard to both flight times and knee angles. Where appropriate, trendlines have been added to the data to show relationships. Extra lines have been used to show boundaries of judging to highlight meaningful values, in terms of what proportion of judges detected non-compliance with Rule 230.2. These boundaries are based on the proportion of judges required in the IAAF World Athletics Series and Olympic Games to award a red card to disqualify an athlete (three out of eight: 37.5%, red dashed lines), with the lower limit set at a proportion of less than one out of eight (<12.5%, green dashed lines) to indicate a very low likelihood of detection.

Figure 1 shows the detection rates for flight time for all 85 participants in the judging part of the study (each data point represents each analyzed athlete). The result from the regression analysis showed that the detection rate was: 13.0 – 1253 × flight time + 36315 × flight time^2 [$F_{(2, 17)} = 25.68$, $p < 0.001$, $R^2 = 0.75$]. The green dotted line shows that those flight times shorter than 0.033 s (six athletes) were detected by fewer than 12.5% of judges and are therefore likely to indicate non-visible loss of contact. Most flight times that were approximately between 0.040 and 0.045 s were in a detection zone where a proportion of one or two judges detected loss of contact, but not more than three out of eight. Very long flight times (≥0.060 s) were detected by more than 85% of judges.

Similar results from the regression analysis were found for each Level of judge (**Figure 2**): Level III—$F_{(2, 17)} = 22.42$, $p < 0.001$, $R^2 = 0.73$; Level II—$F_{(2, 17)} = 24.10$, $p < 0.001$, $R^2 = 0.74$; Level I—$F_{(2, 17)} = 18.75$, $p < 0.001$, $R^2 = 0.69$; no qualifications—$F_{(2, 17)} = 21.13$, $p < 0.001$, $R^2 = 0.71$. The most noticeable difference between the groups was that nearly 50% of Level III judges and 60% of Level II judges detected loss of contact in the athlete with ∼0.055 s flight time, whereas for the Level I judges and those with no qualifications, it was between 18 and 32%.

Figure 3 shows the mean time taken for all participants to make their decision for each video in terms of the individual flight times measured. The time to detection was: 8.5 + 1235 × flight time – 13382 × flight time^2 [$F_{(2, 16)} = 11.61$, $p = 0.001$. $R^2 = 0.59$], with its peak occurring at 0.046 s.

Figure 4 shows the detection rate for knee angles for each Level of judge for each individual athlete; the horizontal axis shows the values for knee angle at both first contact and midstance. Nearly all athletes increased the knee angle after first contact, and all but one had hyperextended knees at midstance. In general, bent knees were most likely to be identified when the first contact angle was 179° or below. Because racewalking is a continuous movement, it is not possible to identify precisely whether the midstance angle affects perception of the knee's

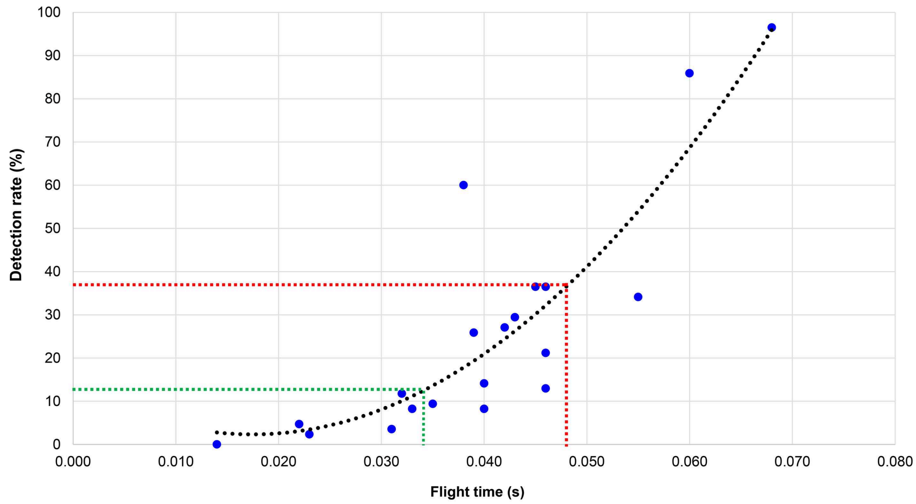

FIGURE 1 | Detection rates for flight time for all 85 participants in the judging part of the study.

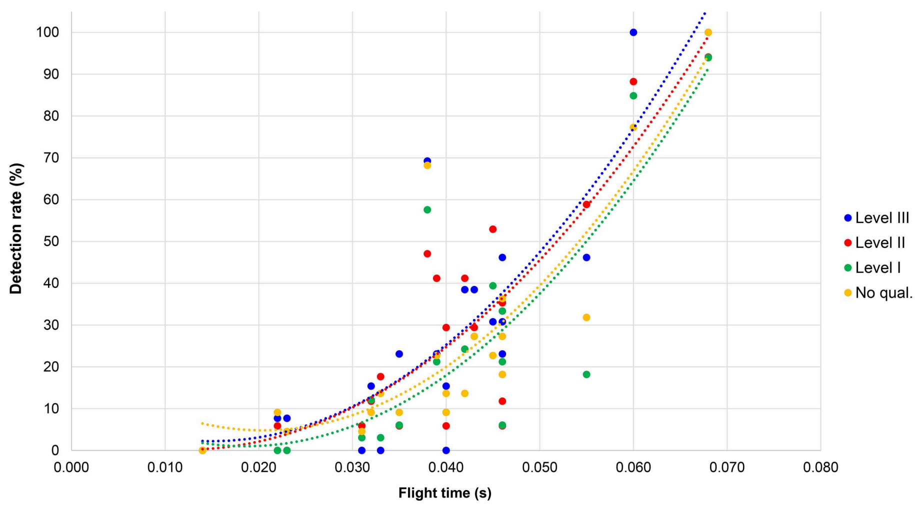

FIGURE 2 | Detection rates for flight time for each group of judges by level.

appearance at first contact. However, it was interesting to find that one athlete with a knee angle of 175° at first contact (on the far right of **Figure 4**) was not detected for bent knees, and it is possible that this was because this athlete's knee hyperextended to 186° by midstance (this athlete also had the shortest measured flight time). In addition, the detection rate for one other athlete (second from the right-hand-side of **Figure 4**) who had bent knees at both first contact (175°) and midstance (178°) was relatively low. In this athlete's case, the flight time was highest of all athletes and the detection rate for loss of contact was very high (100% amongst Level III judges). These two athletes' results can therefore be considered outliers regarding detection of bent knees, and are removed from **Figure 5**, which shows the detection rates for all judges for knee angles at first contact ($r = 0.70$, $p = 0.001$). So that they appear in a similar format to the flight time data (with more "legal" values found on the left of the scale), the knee angles are presented with hyperextended values on the left and decrease along the horizontal axis, and the correlation values reported below are represented as positive values.

Level III judges were the best at making correct calls for knee straightness ($r = 0.79$, $p < 0.001$) (**Figure 6**), in that they were more accurate at detecting bent knees when they did occur, and more accurate at correctly identifying legal knee straightness (i.e., lower bent knee detection rates for knees when they were straight). Level II and Level I judges were roughly equal in their ability to make correct knee decisions ($r = 0.67$, $p = 0.002$ and $r = 0.62$, $p = 0.006$, respectively). However, those respondents without any judging qualifications were poor at this task ($r = 0.17$, $p = 0.507$), in that they did not differentiate between those with bent knees and those with legal knees (up to 183° extension;

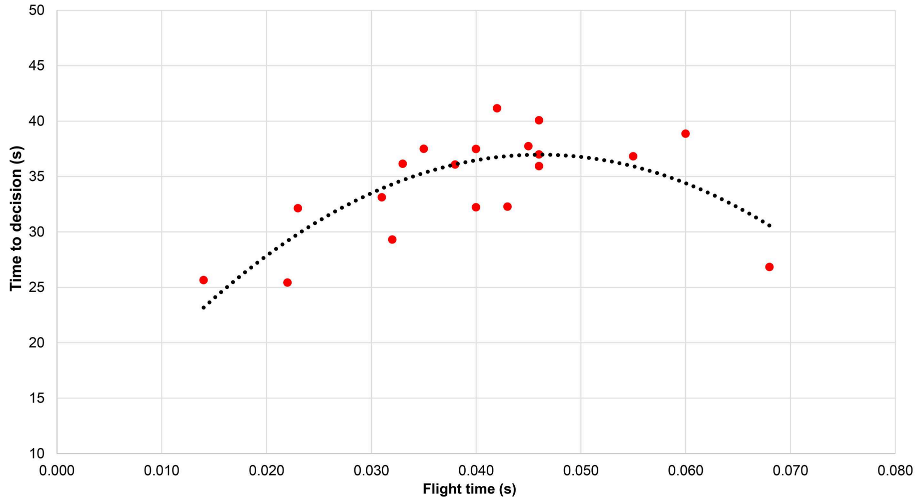

FIGURE 3 | Mean time taken by all participants to make their decision for each individual (indicated by their flight time).

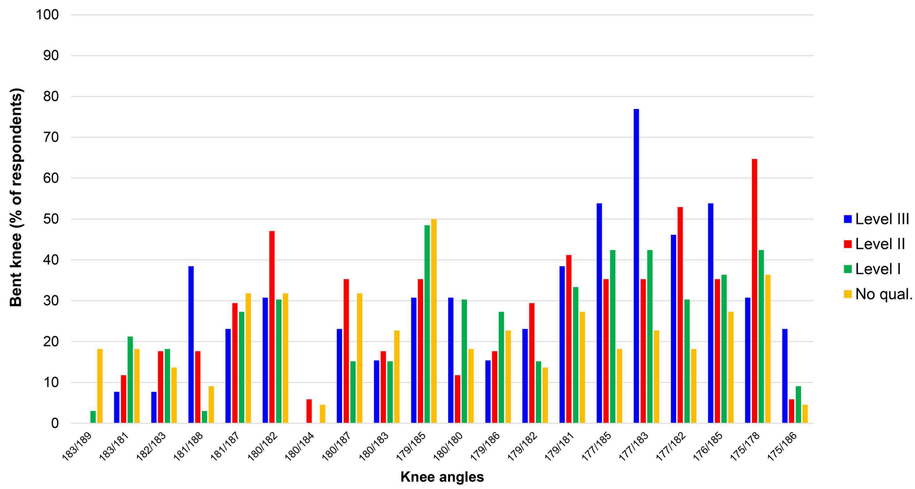

FIGURE 4 | Detection rates for knee angles at first contact and midstance for all 85 participants in the judging part of the study.

i.e., hyperextension). There was no correlation between knee angle and the time taken to make a decision.

In the separate part of the study on the effects of increased racewalking speeds, flight time increased between each successive speed amongst the men ($p < 0.05$, $d \geq 0.61$) (**Figure 7**); however, there was no difference between 14 and 15 km/h. All other variables increased between successive speeds for men ($p < 0.05$, $d \geq 0.61$). Amongst the women, all variables increased between successive speeds ($p < 0.05$, $d \geq 0.61$) except for step frequency, which did not change between 11 and 12 km/h.

DISCUSSION

The aims of this study were first to analyze racewalking judges' accuracy in assessing technique and, second, to measure flight times across a range of speeds to establish when athletes were likely to lose visible contact. The study confirmed that, as occurs in elite-standard competition, each athlete had some flight time, replicating what has been shown in biomechanical research in competition (Hanley et al., 2014) and in laboratory testing (Hanley and Bissas, 2017). One key finding was that loss of contact was detected at similar rates for all groups, regardless of judge qualification status. This indicates that the inability to detect loss of contact below ~0.045 s is normal and representative of the human visual system. This finding concurs with the previous findings of Knicker and Loch (1990) and De Angelis and Menchinelli (1992) and emphasizes that the human eye cannot detect very short flight times. It also suggests that 0.040–0.045 s is an appropriate threshold to adopt as "visible loss of contact" in the absence of judges when coaches are testing athletes using electronic aids. By contrast, very low detection rates occurred when flight time lasted <0.033 s. Judges also took longer to

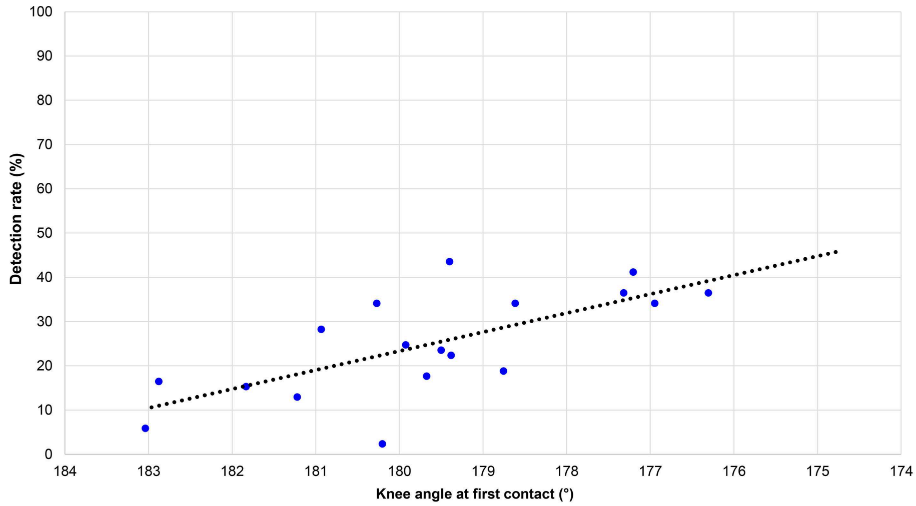

FIGURE 5 | Detection rates for knee angles (first contact) with two outliers removed for all 85 participants in the judging part of the study.

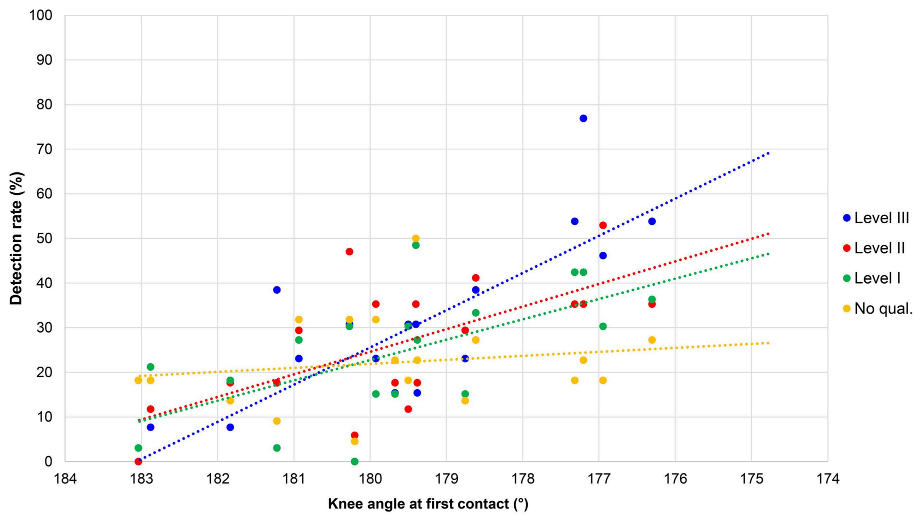

FIGURE 6 | Detection rates for knee angles (first contact) for each group of judges by level.

make a decision when flight times were ∼0.045 s and showed the need for judges to observe athletes on several occasions to make a decisive judgement, as is normal during a race. It is worth bearing in mind that the presented results were collecting using an experimental design in laboratory-based conditions. Although the results showed that most athletes (65%) had flight times between 0.03 and 0.05 s, indicating that these are the ranges typically adopted by well-trained racewalkers, the threshold of ∼0.04 s for visible loss of contact that we (and previous research) found might not apply in race conditions where, for example, there are frequently large groups of athletes and judges' views are obstructed. Additionally, racing conditions differ from the laboratory because of weather conditions (e.g., bright sunlight, heavy rain), surface levelness, and racewalkers' motions that can deviate from a straight line. For training purposes, or for assessing judges in competition, technology could help, for example, by using a video camera to record athletes as they pass judges' positions (Hanley et al., 2018).

Any coaches who use technology should consider that modern racewalkers typically have flight times across a range of competitive speeds (from 0.01 to 0.05 s, approximately). Laboratory and field-based technology that is currently used to measure flight times includes force plates, high-speed video cameras, infrared optoelectronic systems, LED-based hardware, pressure insoles, and inertial sensors (Di Gironimo et al., 2017). Those systems that are external to the athlete (e.g., video cameras) have the advantage of being controlled by the coach or scientist without interfering with the athlete's movements

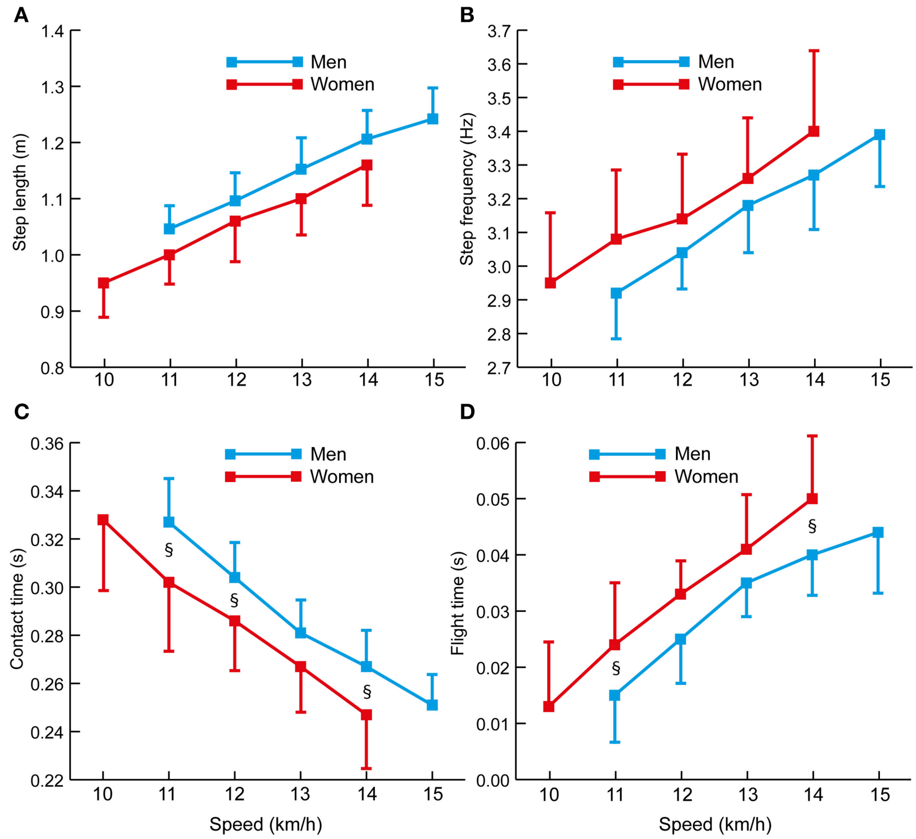

FIGURE 7 | Changes in spatiotemporal variables with increased speed in men and women racewalkers: **(A)** step length, **(B)** step frequency, **(C)** contact time, and **(D)** flight time. Results are shown as means, with SD indicated as plus or minus for either group for clarity. Differences between men and women ($p < 0.05$, $d \geq 0.61$) are indicated with the § symbol.

(e.g., that inertial sensors might do). Technology for adjudicating on critical incidents has become more widespread in high-performance sport (e.g., cricket, football, and tennis). However, it should be noted that any introduction of technology to judge loss of contact from 2021 will require changes in racewalking techniques, which will have implications for athletes and their coaches, especially if the technology's threshold is set much differently from what the human eye is capable of. Care should be taken amongst coaches that training for the event does not become focused on any technology used and how to work within it, at the expense of the biomechanical or physiological optimization of movement.

The results showed that, as expected, fewer athletes were considered to have bent knees when the knee angle was larger (angles above 180° are hyperextended and abnormal in normal walking and running). Fewer than 20% of respondents considered knee angles above 181° to be bent, with a boundary of 177° as the lower limit for bent knee detection (i.e., more than 37.5% of judges). This effectively shows that knee straightness is considered to occur at angles above 177°, which is very close to the geometrical definition of a straight line (180°). In contrast to the detection rates for loss of contact, however, there was a clear difference between Levels of judge with regard to detection of knee infringements. There is no precise definition of what constitutes "straightened" or "bent" knees within IAAF Rule 230.2, and thus it is not a simple case of measuring a knee angle and comparing it to a standard value. Nonetheless, within this inexact definition, Level III judges were the best at judging knees, in that they were more likely to detect anatomically bent knees and less likely to indicate bent knees when they did not occur. Level II judges were also good at making correct decisions regarding knees, with little difference from Level I judges. By contrast, those who had no judging qualifications made both Type I errors (detecting bent knees when they did not exist) and Type II errors (not detecting bent knees when they did exist). The role of the judge is vital to racewalk competitions and their abilities to detect infringements can be improved, as shown by the better detection rates of higher qualified judges. Whereas, the detection of short flight times is more difficult when using the human eye because of its natural inability to detect very brief stimuli, judging knee infringements has been shown to be a skill more readily learned and a key area for future judge education. In this regard, judging racewalking is a serial visual search task, i.e., the judge has to scan the racewalkers to detect infringements, which is a task that is made more difficult when athletes racewalk in large groups (e.g., in big competitive fields like the World Race

Walking Team Championships). Future scientific studies on racewalk judging could consider using eye-scanning technology to identify what the best judges are looking at when making correct decisions, with the results accrued used in future judge education. This will be especially important given the better detection rates of Level III judges in terms of bent knees, and some instances of more accurate detection of flight times of certain athletes by Level II and Level III judges.

For the athletes analyzed in the part of the study that required them to adopt a range of speeds, it was clear and unsurprising that flight time increased as racewalking speed increased: for the men from 0.015 s at 11 km/h to 0.040 s at 14 km/h and 0.044 s at 15 km/h, and for the women from 0.013 s at 10 km/h to 0.041 s at 13 km/h and 0.050 s at 14 km/h. It was noticeable that women had longer flight times than men at 14 km/h, even though there were no differences in step length or step frequency, and women might therefore be at a greater risk of visible loss of contact at racing speeds than men. This does not mean that flight time cannot be reduced by an athlete, and indeed the men did not have longer flight times at 15 km/h than at 14 km/h, suggesting that better technique can be achieved at faster speeds that the athlete has become accustomed to in high-intensity training and competition. At the relatively "safe" racewalking speed of 14 km/h, the men had step lengths and step frequencies of ∼1.20 m and 3.25 Hz, respectively; similarly, for women at 13 km/h, their step lengths and step frequencies were ∼1.15 m and 3.25 Hz. Athletes who wish to race faster, with spatiotemporal values greater than these, must ensure that they simultaneously develop technique to avoid increasing flight time. Additionally, the values give an indication as to the effect of any particular threshold for loss of contact (using appropriate technology) on racewalking speed to athletes, coaches and administrators. However, the results do not indicate that it is not possible to achieve faster times with no loss of contact whatsoever (the athletes were not instructed to attempt this), and therefore a different approach to technique could allow for less or no loss of contact.

Overall, the results showed that responses were quicker when the racewalker had either a very short flight time (invisible to the human eye) or a very long one. It took longest for judges to decide whether loss of contact occurred when the flight times were ∼0.045 s, which as described above was about the threshold for clear loss of contact to the human eye. In practice, decision times of 40 s meant watching the video three or four times, whereas the quicker decisions (<30 s) required two or three views only. Judges therefore do need to observe athletes on more than one occasion during a competition before deciding to write a red card, and supports the current practice of showing a yellow paddle before issuing a red card (apart from in exceptional circumstances), as well as the practice of viewing each video three times during IAAF judge examinations. Coaches should also remind their athletes to adjust their technique when a paddle is shown, or when a warning is indicated on the board, as many ignore these valuable sources of feedback (Alves et al., 2018). Two outlying, or at least unusual, results were found in the detection of bent knees. One of these athletes was probably judged to have been legal given the knee angle increased to a hyperextended position of 186° by midstance, and the other athlete had a very long flight time (0.068 s). It is probable that, in this latter example, the judges detected flight very readily and did not concern themselves about knee angles. In actual competition, such a decision would be very natural given that judges can award only one red card to an athlete, and making such an easy decision is of benefit when judges have to observe many athletes in any particular race.

The format of this study was similar to how IAAF judging examinations (video component) are conducted: prospective members of the IAAF judging panels watch a series of 20 videos and are asked to indicate whether each identified athlete is racewalking legally. The main differences were that, in this study, judges could view the videos repeatedly, rather than a set number of times; the athletes racewalked in a laboratory, rather than in competition; and the athletes were filmed individually, rather than in a group (the IAAF judging videos comprise a mixture of individual and group shots). These limitations of the videoing process in this study were necessary to ensure that valid and reliable data were obtained from the force plates and high-speed camera. As stated above, the nuances of competition, such as the race surface, presence of large groups, and weather conditions, can all affect a judge's perception of the racewalkers' movements. In addition, judging in competitive situations has a real effect on the athlete (possible disqualification) and judges need to be completely sure that the athlete has infringed; in our study, there was no such pressure to be cautious and judges might have been more disposed to indicate perceived rule infringements. Because of these differences, research that compares these video-based decisions with "live" decisions made during competition would be invaluable, not just to evaluate any introduction of technology but also to evaluate the video-based assessments currently adopted in IAAF judge evaluation and selection. Accordingly, follow-up studies on racewalk judging could involve measurements taken with appropriate technology during competitions across different standards. Despite our best efforts to contact all appropriate participants, it was nonetheless difficult to recruit a large sample of judges (partially because the actual number of judges in the IAAF Level II and Level III panels is restricted to only the best judges) and future research should try to ensure as many judges as possible are involved.

CONCLUSIONS

This was the first study to analyze the detection rates of a large number of qualified IAAF racewalking judges from around the world. On average, racewalkers had flight times across a range of speeds, and all Levels of judge had higher detection rates when flight time exceeded 0.045 s, and lower ones below 0.033 s. With electronic chip insole technology being currently developed, these values give a guide as to the realistic visual threshold of judges that could be replicated with technology; for coaches, the important finding was that these thresholds corresponded to racewalking speeds of ∼14 km/h for men and 13 km/h for women. One of the most important findings was that there was little difference between Levels of judge in terms of detecting flight time, as the human visual system is unable to detect very brief loss of contact, regardless of judge qualification. In some instances of moderate loss of contact in an individual athlete, Level II and Level III judges had higher rates of detection, and indicates that for certain techniques, a degree of learned skill is involved. Study participants with no judging qualifications were as likely to decide that legal racewalkers were breaking the knee part of Rule 230.2 as much as those who had much more bent knees, whereas Level III judges were the best in this regard. Given it is proposed that insole technology is adopted to measure loss of contact, it is vital that world and national governing bodies strengthen the education of judges with regard to the identification of bent knees in particular, which were the sole reason for the disqualification of six athletes from the 2017 IAAF World Championships.

DATA AVAILABILITY

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

All human subjects were treated in accordance with established ethical standards. The protocol was approved by the Carnegie School of Sport Research Ethics Committee. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The subjects were provided with Participant Information Sheets, and in accordance with the Carnegie School of Sport Research Ethics Committee's policies for use of human subjects in research, all subjects were informed of the benefits and possible risks associated with participation and informed of their right to withdraw at any time.

AUTHOR CONTRIBUTIONS

BH, CT, and AB conceptualized and designed the study and wrote the manuscript. BH and CT conducted the data collection and analyses and created figures and tables. All authors read and approved the final manuscript.

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Optimal Development of Youth Athletes Toward Elite Athletic Performance: How to Coach Their Motivation, Plan Exercise Training, and Pace the Race

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Elite athletes have invested many years in training and competition to reach the elite level. One very important factor on the road to elite performance is the decision-making process regarding the regulation of effort over time, termed as pacing behavior. The regulation of effort is vital for optimal athletic performance during a single race and over a longer period of time (e.g., a competitive season) as an inadequate regulation could result in a higher risk of injuries, overtraining, and drop-out. Despite this, there is limited knowledge on how young athletes learn and develop the abilities related to pacing. Pacing behavior of athletes develops from childhood throughout adolescence and is thought to be closely connected to physical maturation, the development of pre-frontal cortical related (meta-) cognitive functions, as well as the gathering of experience with exercise tasks. The motivation of an athlete can critically influence how an athlete paces a single race, but also how they distribute their effort over a longer period of time. Coaches are advised to closely monitor the development of pacing behavior during adolescence (e.g., by gathering split times, and related physiological measurement, during training and competition), as well as the underlying factors including physical maturation (meta-) cognitive development and the motivation of young athletes. Furthermore, pacing behavior development could be aided by providing training in which the task, individual, and environment are manipulated. Hereby, presenting athletes with the opportunity to gain experience in situations which closely resemble the perceptual-motor conditions of upcoming competitions.

Keywords: pacing, performance, youth, motivation, monitoring, training

INTRODUCTION

The athletes performing at the 2019 IAAF world championships represent the elite of the athletics community. Despite there being multiple pathways toward achieving elite athletic performance in adulthood, the dedication of these athletes might be best exemplified through the amount of time spent on training and improvement (Ericsson et al., 2018).

The longevity of this dedication is vast, with published reports indicating that elite athletes may commence participating in athletics from childhood (6–7 years old), yet the mean age of peak performance of these elite athletes ranges from 24.5 to 29 (Haugen et al., 2018). Through these many years of development, a multitude of skills are to be acquired and refined by expert athletes. Failure to acquire or refine certain skills could be the reason why some junior champions fail to win as adults. One of those skills, relevant to current and future athletic champions, currently experiences a vast increase in attention from the academic world: pacing.

Pacing is defined as the goal-directed distribution of energy over a pre-determined exercise task (Edwards and Polman, 2013), a process of decision-making regarding how and when to expend energy (Smits et al., 2014). The outcome of this process is termed the pacing behavior of the athlete (Smits et al., 2014). Previous literature concerning pacing has generally focussed on analyzing the effects of the energy distribution of athletic performance. In athletic disciplines in which the performance time is under 30 s (e.g., 100 and 200 m sprints), the most beneficial distribution of energy seems to be an all-out burst (Abbiss and Laursen, 2008). During an 800 m event, elite adult athletes exhibit a pacing behavior in which the velocity decreases over the race (Hettinga et al., 2019). During the longer events (1,500 m, 5-km, 10-km and the marathon), elite adult athletes exhibit a pacing behavior in which the velocity increases over the race (Hettinga et al., 2019). Additionally, in the longer the event, there seems to be a greater requirement to more evenly distribute energy resources over the race, as the race distance increases (Hettinga et al., 2019). The pacing behavior of athletes is influenced by the specific nature of the task (Hettinga et al., 2009; Stoter et al., 2016), factors associated with the individual athlete (Micklewright et al., 2010; Williams et al., 2014), and the environment (Hettinga et al., 2017; Konings and Hettinga, 2018). While the majority of research regarding pacing behavior focuses on the relation between pacing behavior and performance during a single race or event, adequate energy distribution over longer time periods should also be considered (Edwards and Noakes, 2009). For example, the distribution of effort over a training session, tournament, season or even a 4 year Olympic cycle, could influence (current and future) performance as well as injury and drop-out rate (Schiphof-Godart and Hettinga, 2017). The long term distribution of effort is suggested to be related to the motivation and drive of the athlete (Schiphof-Godart and Hettinga, 2017). Although an athlete's drive can function as a strong motivator, it can also push athletes toward a less than ideal distribution of energy. It is thus of crucial importance to guide and coach athletes toward developing adequate pacing behavior, which will allow them to perform to the best of their ability while staying healthy, engaged and injury-free.

Although the pacing behavior of elite senior athletes has been studied extensively in the last 30 years, there is limited understanding of the processes underpinning the acquisition of pacing skills in developing junior athletes (Elferink-Gemser and Hettinga, 2017). This is remarkable, as it has previously been put forward that the skill to adequately distribute energy to achieve an exercise goal is not fully innate, but develops relative to the (meta-) cognitive and physical attributes of an individual (Micklewright et al., 2012) as well as the amount of experience an individual has with an exercise task (Foster et al., 2009). Adolescence is a period in which there are changes in an athletes physical attributes and (meta-) cognition (Beunen et al., 1992; Blakemore et al., 2010). Additionally, during the adolescent time period, many athlete programs increase the amount of training and competition, providing athletes with more opportunities to gather experience with an exercise task. Indeed, the small number of studies which have investigated the development of pacing behavior in junior athletes see a development of behavior during adolescence (Wiersma et al., 2017; Menting et al., 2019b). Despite these findings, previous research has focussed more on how the pacing behavior of elite senior athletes resulted in optimal performance, and much less so on the process of how junior athletes acquire and develop the skills to optimally pace a race (Hettinga, 2018). With pacing behavior being vital to successful performance (Konings and Hettinga, 2018), it is important to develop our understanding of how the complex skills associated with adequate energy distribution are developed across the developmental continuum. Therefore, this perspective aimed to investigate the development of pacing behavior of young athletes, specifically during adolescence. The current perspective does not only describe how does pacing behavior develop in young athletes, but will also answer additional related questions, including: what are the underlying mechanisms of pacing behavior development during adolescence? How does the motivation and drive of the athlete impact the distribution of effort in the long term? And lastly, how can coaches monitor and train pacing behavior development in elite athletes of the future?

THE DEVELOPMENT PATHWAY OF PACING BEHAVIOR

A logical first step would be to map the process of pacing behavior development in athletes. It should be pointed out that although pacing behavior is influenced by the characteristics of the performed exercise task, a more general pacing skillset is present in all athletes, regardless of the specific sport they participate in (Elferink-Gemser and Hettinga, 2017). Therefore, in discussing the development of pacing behavior in athletics, we should not exclusively take into account research that focuses on athletic disciplines, but also on other sports and particularly studies exploring younger individuals (**Table 1**).

Although the literature on pacing in children and youth is scarce, studies suggest that the pacing behavior of 5–8 year old children, performing an $\sim$4 min running task, is characterized by a decrease in velocity over the duration of the task, pointing to a lack of skill to anticipate the demands of the running task and a difficulty in setting initial exercise pace (Micklewright et al., 2012). At $\sim$10-years of age, observed pacing behavior shifts toward a U-shaped velocity distribution, suggesting that children of this age develop the ability to hold back an energy reserve in order to achieve the set exercise goal (Micklewright et al., 2012; Lambrick et al., 2013). In long-track speed skating (1,500 m), the pacing behavior of elite adult

TABLE 1 | Studies investigating pacing behavior in children and junior athletes.

Study	Study design	Sport type	Exercise type	Age group	Main findings
Micklewright et al., 2012	Experimental (cross-sectional)	Run	Time trial (450 m) (600 m) (750 m) (900m)	5.6 ± 0.5 year 8.7 ± 0.5 year 11.8 ± 0.4 year 14.0 ± 0.0 year	Between 9 and 11 years of age, the pacing behavior of schoolchildren develops from a negative pacing behavior, indicating an inability to anticipate exercise demand, toward a more conservative U-shaped pacing behavior, indicating an energy reserve.
Lambrick et al., 2013	Experimental (cross-sectional)	Run	Time trial and head-to-head (800 m)	9–11 year	Unexperienced children presented a *U*-shaped pacing behavior, indicating an energy reserve. Performance was decreased by the introduction of an opponent.
Deaner and Lowen, 2016	Experimental (cross-sectional)	Run	Head-to-head (5,000 m)	High-school athletes	Male runners showed a greater slowing from the first to the second mile of the race, compared to female runners.
Wiersma et al., 2017	Experimental (longitudinal)	Long-track speed skating	Time trial (1,500 m)	U15 U17 U19	The pacing behavior of junior skaters develops, toward a relatively slower start and final round, and a relatively faster mid-section, throughout adolescence. Skaters who reached the elite level as adults exhibit a pronounced development of pacing behavior at a younger age, compared to sub-elites and non-elites.
Menting et al., 2019b	Experimental (cross-sectional)	Short-track speed skating	Head-to-head (1,500 m)	U17 U19 U21 Adults	The pacing behavior of youth skaters changes during adolescence, toward the conservative behavior exhibited by adult skaters. Female skaters tend to adopt the pacing behavior of adult skaters earlier compared to male skaters.
Menting et al., 2019a	Review	Swimming	Head-to-head (200 m)	Junior: 16.9 ± 2.1 year	- Junior swimmers exhibit a more variable pacing profiles compared to adults.
			(400 m)	Adult: 22.8 ± 2.9 year −18.2 ± 2.0 year	- Junior swimmers exhibit difficulty in selecting the most beneficial pacing strategy before a race.

skaters is characterized by a relatively slow start and a fast 700–1,100 m section. At ∼15–16 years of age, there is a relatively large shift in the pacing behaviors of junior speed skaters, in which their pacing behavior becomes more closely aligned with the pacing behavior exhibited by adult skaters (Wiersma et al., 2017). Furthermore, junior skaters who exhibit a more conservative pacing behavior, as typically seen in adult skaters, earlier on in their career, will reach a higher performance level during adulthood (Wiersma et al., 2017). Junior short-track speed skaters show a similar development, as their pacing behavior shift during adolescence, to resemble the typically conservative pacing behavior seen in adults, featuring a relatively slow start and fast final laps. Additionally, during adolescence, junior short-track speed skaters learn to adequately integrate environmental cues (e.g., opponents) in their pacing behavior (Menting et al., 2019b). Lastly, a difference in the development of pacing behavior during adolescence was observed between sexes, with female short-track speed skaters displaying the development toward the conservative pacing behavior of adult skaters, earlier in their development process (Menting et al., 2019b). Similarly, female high school athletes exhibited less slowing down between the first and second mile of a 5 km run, compared to their male counterparts (Deaner and Lowen, 2016). Research in elite adults athletes shows that higher performing athletes are characterized with less slowing down during a race (Hanley, 2014), indicating that female high school runners exhibit a more mature pacing behavior compared to males. In swimming, the pacing behavior of swimmers going through adolescence becomes less variable, and swimmers improve their ability to plan their pacing strategy before a race (Menting et al., 2019a). Summarized, the developmental period starting at 10-year of age, and going through adolescence, presents major shifts in pacing behavior in a multitude of sports. The development of pacing behavior is different between the sexes and is (in speed skating) linked to the performance level an athlete reaches as an adult. There are currently no studies investigating the development of pacing behavior in junior athletes in athletic disciplines. However, the occurrence the above described pacing behavior development in a variety of endurance sports would suggest that there is a large chance that the pacing behavior of athletes in athletic disciplines would also develop during adolescence. Therefore, future research is warranted to investigate how the task characteristics of different athletic disciplines influence the above described development of pacing behavior in junior athletes competing in these disciplines.

UNDERLYING MECHANISMS OF PACING BEHAVIOR DEVELOPMENT IN YOUTH ATHLETES

The pacing behavior of athletes seems to go through a development during adolescence (Elferink-Gemser and Hettinga, 2017). It is also a period in life when athletes experience their adolescent growth spurt. Girls attain their maximum peak height velocity around 12 years of age, in contrast to boys who are on average about 14 years old (Malina et al., 2004). Adolescence is marked by physiological transformations as well. For example: the left ventricular mass (LVM), which is an important morphological characteristic of the heart (de Simone et al., 1998), is similar in boys and girls until age 9–12 years, but afterwards grows faster in boys, even when expressed relative to body mass (De Simone et al., 1995). Furthermore, the hematological components of oxygen delivery and the oxidative mechanisms of the muscles are also related to body dimensions and muscle mass (Armstrong and Welsman, 2001; Eisenmann et al., 2001), and will therefore be under development during adolescence. The interplay between all these various developing physical attributes influences athletic performance as well as sport-related behavior such as pacing (Elferink-Gemser et al., 2011). The difference in maturation could possibly be the underlying reason for the previously mentioned phenomenon that female athletes adopted the pacing behavior of adult athletes earlier in their development compared to their male counterparts. Maturing athletes will need to adapt their pacing behavior to their developing physical abilities (Elferink-Gemser and Hettinga, 2017). As female athletes mature at a younger age, they could be further along in this adoption process compared to males of the same age. Tracking of maturation status is already part of the talent developmental strategy advised by the IAAF (Dick, 2013). However, the impact of physical maturation on athlete's pacing behavior is still unexplored in literature and could provide opportunities for future research.

Adolescence is not only a time of physical maturation, but also a period of cognitive development. As pacing is essentially a self-regulatory skill, it stands to reason that its development is closely connected to the development of cognitive skills self-regulation of learning (Brick et al., 2016; Elferink-Gemser and Hettinga, 2017). According to prominent authors, self-regulatory skills are comprised of meta-cognitive functions such as the ability to reflect, plan, monitor, and evaluate a goal-directed process as well as aspects of motivation and self-efficacy (Zimmerman, 2006; Jonker et al., 2010). It has been widely accepted that gathering experience of a task positively influences pacing behavior and performance (Foster et al., 2009; Mauger et al., 2009; Micklewright et al., 2010). Elferink-Gemser and Hettinga (2017) suggested that experience gathered during training and competition calibrates and improves the self-regulatory skillset and therefore an athlete's pacing and performance. Moreover, athletes with a higher meta-cognitive skill level were said to make more efficient use of training and competition, extrapolating more learning from a training session, which could then lead to an improvement in pacing behavior and performance (Elferink-Gemser et al., 2016; Jonker et al., 2019). More recently, it has been proposed that core executive functions support the top-down self-regulatory processes involved in pacing by sustaining attention to the planned goal, the inhibition of distractions to the goal and the adaptation of the pacing behavior as a result of external factors (Hofmann et al., 2012; Hyland-Monks et al., 2018). Adding to the rationale of the relation between the self-regulatory skillset and executive functioning in the case of pacing behavior, is the fact that both are closely linked to the pre-frontal cortex (Elferink-Gemser and Hettinga, 2017; Hyland-Monks et al., 2018). The pre-frontal cortex is an area of the brain responsible for planning and decision making, and actively develops throughout adolescence (Casey et al., 2008). Therefore, it seems realistic to assume that the development in pacing behavior witnessed during adolescence could be, at least partially, ascribed to the development of the pre-frontal cortex as well as the increase in exercise experience, influencing the meta-cognitive self-regulatory skills and core executive functions of developing athletes. Following this rationale, developing elite athletes should be encouraged to compete in high level competitions in order to gather experience and calibrate their pacing skillset, emphasizing the importance of the IAAF organized under 18-, under 20- and Youth-championships. In other sports disciplines such as football and speed skating, the monitoring and training of (meta-) cognitive skills is starting to become integrated in talent development and selection programs (Toering et al., 2012). The importance of the relation between (meta-) cognitive skills and the development of pacing behavior and endurance performance presents new opportunities for scientific research, talent development, and coaching in athletics.

COACHING PACING BEHAVIOR OF YOUTH ATHLETES: MOTIVATION AND THE DRIVE TO PERFORM

Motivation defines athletes' willingness to exert effort during training and competition (Schiphof-Godart and Hettinga, 2017), and needs to be sufficient for enduring a vast amount of training hours (Mallett and Hanrahan, 2004; Gulbin et al., 2010). Research has shown that the motivation of athletes impacts the sensation of fatigue during exercise, therefore influencing how an athlete paces the exercise (Gibson et al., 2003). Moreover, motivation has previously been described as an important component in the self-regulatory learning process (Zimmerman, 2006), and is therefore also expected to be important in pacing behavior development (Elferink-Gemser and Hettinga, 2017). It therefore seems that motivation is a key factor in pacing behavior and should be considered in the framework of pacing behavior development. Although there is currently no literature explicitly studying the impact of motivation on pacing behavior development in youth athletes, lessons can be learned from more general literature regarding motivation, and applied to the coaching of youth athletes.

As pacing is essentially a goal-oriented self-regulatory process, pacing behavior is influenced by the importance of success regarding the goal of the task (Edwards and Polman, 2013; Zimmerman et al., 2017; Wolff et al., 2019). Modifying either an athlete's perception of the importance, probability or controllability of successfully achieving the goal of a task, will thus modify pacing behavior through increased or decreased motivation (Rhoden et al., 2015; Wolff et al., 2019). Factors such as false or deceptive feedback (Williams et al., 2014), encouragements (Edwards et al., 2018), racing an opponent

(Konings et al., 2016), modifying the salience of the reward or the probability of attaining a given goal (e.g., to be close to one's personal best, to be close to a top-3 ranking or qualification) (Schiphof-Godart et al., 2018) can enhance performance through by adapting pacing behavior. All of these factors modify either the weight of the "costs" of the task or the "reward" of reaching the set goal, hence increasing or decreasing athletes' motivation to exert effort (Schiphof-Godart et al., 2018). Coaches play an important role in that they have a strong influence in the nature and importance of the goals athletes choose, and can thus increase motivation, and influence pacing behavior, by providing realistic goals that can be largely controlled by the athlete (setting a personal best performance), in contrast to goals that may be partly determined by external factors (such as beating an opponent). Additionally, coaches could provide ways in which athletes will reach the set goal, including: imagining the joy of success (McCormick et al., 2019), positive self-talk focusing on a positive outcome (Gibson and Foster, 2007; Hatzigeorgiadis et al., 2018), but also realistic expectation regarding the fatigue and exhaustion an athlete undoubtedly will experience during a race (Baden et al., 2005), thinking in several if-then scenario's providing athletes with an internal locus of control and feelings of autonomy competence and self-efficacy (Howle et al., 2016). These methods could all lead to increased motivation and potentially assist in optimizing an athletes' pacing behavior. In the long term, sustaining motivation for their sport might be much easier to sustain when athletes like what they do (intrinsic motivation) and feel as if their active participation in sport is an important part of their identity (harmonious passion) (Vallerand et al., 1987; Ryan and Deci, 2000). Athletes who score highly on measures of intrinsic motivation and/or harmonious passion for their sport will be more inclined to spend their energy toward achieving long-term benefits over short term outcomes (such as success) and choose to train in situations that increase their future skills instead of augmenting their immediate chances of winning (Vallerand et al., 1987; Ryan and Deci, 2000). These athletes are likely to base their long term goal-directed energy distribution more on task-oriented goals, aiming at increasing their own performance rather than outperforming others (Pensgaard and Roberts, 2000). This will also affect the athlete's reaction to feedback: task-oriented and intrinsically motivated athletes will welcome feedback and use it to their benefit (Ryan and Deci, 2000; Biddle et al., 2003; Watson et al., 2011). They will see it as an occasion to improve their performance, will react positively (hence increasing the chances of coaches providing feedback) and increase their skills in learning from feedback Factors increasing intrinsic motivation and a harmonious passion for sport are feelings of autonomy, competence and relatedness (Ryan and Deci, 2000; Vallerand et al., 2007). Summarizing, it is advised that in order to optimize pacing behavior development, coaches are advised to monitoring the motivation of their athletes in order to optimize the pacing process, by setting achievable, realistic goals. Additionally, coaches should consider guiding their athletes in developing intrinsic motivation for their sport, by providing them with opportunities to make their own choices, feel competent and be part of a social group with whom they identify and with whom they feel safe and respected.

COACHING PACING BEHAVIOR OF YOUTH ATHLETES: MONITORING AND TRAINING THE DECISION MAKING PROCESS

Monitoring an athlete's pacing behavior, and over a longer time the development of this pacing behavior, has previously been done through three different means. The first is the observation of split times during competitive events. Secondly, during training there is the possibility of monitoring athletes by combining the observation of split times with additional physiological data (e.g., heart rate) and rate of perceived exertion. Lastly, in a controlled laboratory setting, monitoring of power output and the use of different energy systems during exercise can be used to give a detailed description of the pacing behavior of an athlete. Long term monitoring of athletes could, in the future, provide coaches with benchmarks for the development of pacing behavior. In order to monitor the underlying mechanisms related to pacing behavior development, physical maturation (meta-) cognitive development, and the motivation of athletes should be tracked as well. In literature, physical maturation is commonly monitored via the age at peak height velocity, as calculated using sitting height, leg length and body mass (te Wierike et al., 2015). As for the (meta-) cognitive skills associated with pacing behavior development, core executive functions have previously been studied and monitored via a variety of tests, including well known tests such as Tower of London and Stroop task (Jacobson and Matthaeus, 2014). Monitoring of self-regulatory skills in athletes could be done via questionnaires such as the Self-Regulation of Learning Self-Report Scale (Jonker et al., 2010; Toering et al., 2012). As for the monitoring of the motivation of athletes, several questionnaires have been validated and used in research with this purpose, for example: Achievement Goals Questionnaire for Sport (Conroy et al., 2003) or the Behavior Regulation Exercise Questionnaire (Markland and Tobin, 2004).

In addition to monitoring the pacing behavior of athletes, it would be interesting to see how the decision-making processes involved in regulating pacing behavior could be trained. Recent literature suggests that human-environment interactions, such as those experienced when competing against opponents, play an essential role in regulating pacing (Smits et al., 2014; Hettinga et al., 2017; Konings and Hettinga, 2018). The emphasis placed on the human-environment interaction is analogous to contemporary frameworks of sport performance rooted in ecological dynamics (Seifert and Davids, 2017), including the constraints-led approach to skill acquisition (Davids et al., 2008; Renshaw and Chow, 2019). Inherent within these theoretical approaches is the idea that perception and action are causally and cyclically related (Handford et al., 1997; Kugler and Turvey, 2015). In the context of pacing, this concept of perception-action coupling relates to the dynamic process of continuously exploring information from the human-environment interaction to produce the specific affordances (or opportunities for action) that may result in a change of pacing behavior (Smits et al., 2014). Such affordances are predicated by both the perceptual information provided at any given moment in the race (e.g., distance to lead athlete) and the current action capabilities of the individual (e.g., athletes' current physical conditioning/fatigue). Thus, because of the highly dynamic nature of sport, and subsequent human-environment interactions, the development and training of decision making can be viewed as a dynamic and non-linear process (Chow et al., 2013).

From a coaching perspective, the concept of affordances is a central component of the constraints-led approach (CLA) to skill acquisition (Davids et al., 2008). According to proponents of the CLA, it is hypothesized that specific emergent behaviors (e.g., pacing) emerge as a function of three interacting constraints; task (e.g., intensity, loading), individual (e.g., current conditioning, perceived fatigue), and environmental (e.g., heat, altitude) constraints. Through systematically manipulating these constraints, coaches (and athletes) can construct highly representative learning environments to replicate the specific perceptual-motor demands required of athletes to regulate their pace during competition. Due to the centrality of perception-action coupling within the CLA, athletes who have been repeatedly exposed to such highly representative conditions during development (through practice and competition) are thought to develop an adaptable repertoire of perceptual-motor behaviors (e.g., pacing) suited to the dynamic conditions of competition (Pinder et al., 2011; Chow et al., 2013). A practical example can be found in the preparation of athletes for the extreme environmental constraints (e.g., heat, humidity) anticipated at the 2019 IAAF championships in Doha. Of primary concern will be accessing facilities to replicate the specific environmental conditions athletes will face during the championships. Consistent with the CLA, optimal practice conditions will provide athletes with "on-track" race experience against relevant opponents in temperatures like those expected in Doha. For many developmentally elite athletes, directly experiencing these exact conditions is unlikely for many financial and logistical reasons. Consequently, many athletes will be trained in environmental chambers in which the environmental constraints can be externally controlled. While heat acclimatization procedures have been shown to improve physiological performance (Chalmers et al., 2014) the often isolated nature of such training apparatus can result in a decoupling of perception and action. That is, athletes are not exposed to opponents, and are thus less likely to recognize the specific affordances to modify their pacing presented during the dynamic human-environment interactions in extreme environmental conditions. To combat such issues, coaches may utilize innovative methods to increase the fidelity of the practice conditions so that perception and action are more tightly coupled. Recent advances in virtual reality offer exciting opportunities to create immersive and interactive virtual environments, potentially leading to greater decision making transfer to competition through perception action coupling (Craig and Cummins, 2015; Stone et al., 2019). Less expensive methods, such as projecting different competitive scenario's using life size images of opponents using video or avatars on to screens, from the athlete's perspective, may also be advantageous in enhancing perception-action coupling (Savelsbergh et al., 2002, 2010; Croft et al., 2013; Konings and Hettinga, 2018). Despite the potential of such novel training methods, the unique psycho-social environmental constraints experienced by developing athletes attending their first senior world championships is virtually impossible to recreate. Yet, the experience will be invaluable in recognizing the specific affordances to regulate their pacing behavior in future IAAF World Championship events.

CONCLUSION

Pacing vitally impacts athletic performance both during competition and over a longer period of time. It is therefore imperative that young athletes, striving to reach the elite level, adequately develop their pacing behavior. Adolescence is characterized by major shifts in pacing behavior. Pacing can be seen as a self-regulatory skill and the development of pacing behavior during adolescence is thought to be underpinned by physical maturation, the development of pre-frontal cortical (meta-) cognitive functions, as well as the increase of experience with exercise tasks. Motivation impacts self-regulatory learning and is of importance for optimal development of pacing skills. Coaches are advised to monitor the motivation of young athletes and encourage a motivational climate in which realistic goals are set, athletes enjoy their sport, create positive relationships (with coach, staff, and teammates) and value long term decisions over short term success. Monitoring and training the development of pacing behavior, by ways of a constrained led approach, could be the next step in the talent development process. The complexity of pacing behavior development, as well as its essential role in the career of elite athletes, warrants the need for further research. Future studies are needed to establish benchmarks for pacing behavior development of elite athletes in specific athletic disciplines, as well as a further exploration of the underlying mechanisms of the development of the pacing skillset in the elite athletes of tomorrow.

AUTHOR CONTRIBUTIONS

SM wrote the first draft of the manuscript. DH, LS-G, ME-G, FH, and SM wrote sections of the manuscript. All authors contributed to conception and design of the work, drafted it, and revised it critically for important intellectual content. All authors contributed to manuscript revision, read and approved the submitted version. All authors have approved the final version of the manuscript, agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

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REVIEW
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Ten Tips to Hurdle the Injuries and Illnesses During Major Athletics Championships: Practical Recommendations and Resources

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Participating or winning a medal in major track and field (athletics) competitions is the goal of every athlete. However, health problems can impair sports performance and affect this dream. Therefore, we present ten tips to help hurdle the challenges of illness/injury at major athletics championships: (1) Prepare for travel (medical checking, vaccine, time-zone, jet lag, culture, food habits…), (2) Respect athlete characteristics and discipline specificity (sex, endurance/explosive), (3) Educate athletes and their entourages regarding prevention, (4) Vigilance of painful symptoms and subclinical illness markers, (5) Avoid infection risk (washing hands, safe food and drink, avoid contact with sick people…), (6) Train appropriately and optimally (physical conditioning, technical training, load management, and psychological preparation), (7) Health status (history of previous injuries, well-being in the month before championships), (8) Lifestyle (good sleep, regular hydration and nutrition with safe water/food, regular fruits and vegetables, improve recovery strategies…), (9) Environmental considerations (heat, cold, air cleaning, changes or climatic conditions…), (10) Safety (equipment, rules, own-practice in athletics, and extra-sport activities). These ten tips "PREVATHLES" are based on our field experience in addition to existing epidemiological and experimental literature in athletics and other sports. Although there is currently no scientific evidence for their efficacy, sound judgement, and logical practice provide a strong basis, and given the low risk of using them in the benefit/risk balance, we suggest athletes and those around them follow these ten tips to limit the impact of injury/illness on championship performance.

Keywords: health protection, sports injury prevention, illness prevention, track and field, top-level athletes, injury risk, illness risk

INTRODUCTION

Participating at major athletics events, such as Olympic Games, World or Continental Championships, is the goal for all track and field (athletics) athletes, aiming for optimal performance and winning medals. However, these dreams can be affected by health problems that impair sports performance.

During major athletics championships, a significant number of injuries and illnesses have been reported, varying according to the championship type (i.e., world/continental, outdoor/indoor, and/or adult/junior/youth championships), athlete sex and athletics discipline (Feddermann-Demont et al., 2014; Edouard et al., 2015b, 2019b; Edouard et al., under revision). In addition, athlete health status in the month before the championships has been reported to influence the occurrence of new injuries and/or illnesses during the championships period (Alonso et al., 2015; Edouard et al., 2015c; Timpka et al., 2017). These epidemiological results are fundamental to improve the development of more focused injury and illness prevention research and to implement preventative measures based on objective measures of the problem (van Mechelen et al., 1992). Epidemiological data provides useful insight when trying to anticipate medical service provision and to help in the screening of athletes at risk (Edouard et al., 2015a, 2019a,b; Edouard et al., under revision). Alongside surveillance, there is a need to develop prevention measures. Injury and illness prevention involves athletes as well as the team around them such as coaches, managers, family, sponsors, and includes health professionals and governing bodies (International Olympic Committee (IOC) (Engebretsen and Steffen, 2015), International Association of Athletics Federations (IAAF), European Athletics (EA), and national athletics federations) (Edouard et al., 2014, 2015a). People in a wide variety of roles can help decrease illness and injury in athletes.

Therefore, aiming to decrease illness and injury at major athletics championships, and especially at the 2019 IAAF World Championships, there is a need to propose prevention measures. To the best of our knowledge, currently there is no scientific evidence proven by randomized controlled trials or other high-quality studies on the efficacy of injury and illness prevention measures in athletics, especially in the context of major championships. Using an evidence based approach combining evidence from other sports and our experience in athletics, we present ten tips with materials/resources (Barton and Merolli, 2019) that might help to reduce the risk of injury and illness in championship preparation and competition.

PREPARE THE TRAVEL

Major championships often take place outside of the athlete's own country. Consequently, there is a need for travel, which may be short (i.e., a few hours and/or no time zone change) or long (i.e., more than 5 h and/or >4–5 time zone changes). Travel preparation includes different phases, with pre-travel, traveling, destination, and return (Mahadevan and Strehlow, 2017; Lohr et al., 2018).

Before traveling, athletes and their entourage (especially coaches and medical teams) need to be prepared for practical aspects, including the travel schedule, baggage, accommodation, sporting calendar, insurance, etc. They also should be prepared for the medical aspects, such as the vaccine requirements and health operations in that particular destination, in addition to awareness of nutritional habits (i.e., foods and water), environmental conditions (i.e., temperature, humidity, pollution, and altitude), endemic pathogens, sanitation standards, and cultures that they are likely to encounter (Mahadevan and Strehlow, 2017; Lohr et al., 2018). One practical application could be to anticipate the need for extra rooms to isolate unwell athletes.

During the traveling phase it is important to prevent the negative effects of jet lag, such as sleep disruption, fatigue, and dehydration, which can affect health (i.e., impaired immune function and increase illness risk) and sports performance (Manfredini et al., 1998; Schwellnus et al., 2012; Fowler, 2016; Walsh, 2018). In order to minimize jet lag and travel fatigue effects when traveling, especially >4–5 time zones, we suggest (Schwellnus et al., 2012; Fowler, 2016; Mahadevan and Strehlow, 2017; Schwellnus, 2019):

- arrive at the destination at least 1 day early for each time zone crossed,
- before departing, attempt to partially synchronize sleep/wake cycles and meals for a few days,
- during the travel, avoid sleep deprivation, exposure to dry cabin air, and avoid prolonged relatively immobilized positions, and use appropriately screen (i.e., blue light) and dark glasses to help synchronize sleep/wake cycles with that of the destination,
- on arrival prioritize exposure to sunlight and participate at social activities and training sessions as soon as possible according the usual schedule of the destination, and use regular sleeping and eating times appropriate to the arrival schedule.

The use of sleeping medications or melatonin should only be considered after medical prescription, and/or if medications were already used by the athlete. And remember to consider these suggestions also when traveling back home.

RESPECT ATHLETE CHARACTERISTICS AND DISCIPLINE SPECIFICITY

Since Edouard et al. (2015b) reported sex-related differences in injury risk, we suggest the need to consider a sex-related approach in injury prevention measures. Male athletes suffered more thigh, lower leg, hip/groin injuries and muscle strain and muscle cramps, with female athletes experiencing more stress fractures (Edouard et al., 2015b). Thus, injury prevention measures should focus more on functional conditioning, biomechanical improvements, effective regeneration, and workload optimisation, and should target the lower extremity muscles for male athletes, whilst focusing on stress fracture prevention in female athletes.

Athletics is composed of various disciplines with different physical, mechanical, technical, and psychological demands (Edouard et al., 2011, 2015a,b; Feddermann-Demont et al., 2014), which result in different injury patterns (Edouard et al., under revision). During international athletics championships, the highest injury rates were reported in combined events for male and female athletes, and lowest in throws for male and female athletes, as well as race walking for female athletes (Edouard et al., under revision). Injury patterns significantly varied between disciplines for location, type, cause, and severity (Edouard et al., under revision). Thigh muscle injuries were the main injury diagnoses in sprints, hurdles, jumps, combined events, and race walking, in both male and female athletes (Edouard et al., under revision). Lower leg muscle injuries were the main injury diagnoses in marathon, and lower leg skin injury in middle and long distances, in both male and female athletes (Edouard et al., under revision). And trunk muscle and lower leg muscle injuries were the main injury diagnoses in throws in both male and female athletes (Edouard et al., under revision). Consequently, we suggest that (i) championships injury prevention preparation should be discipline-specific, and (ii) local organization and medical teams should take into account such information to anticipate medical service provision for the different disciplines during the competition (Edouard et al., 2018; Edouard et al., under revision).

Higher illness rates have been reported in endurance events compared to explosive disciplines during major outdoor athletics championships (Timpka et al., 2017; Edouard et al., 2019b). This difference was largely due to the higher rate of exercise-induced dehydration/fatigue/hypotension/collapse problems in endurance disciplines (Edouard et al., 2019b). We therefore suggest paying attention to endurance athletes, by taking into account the environmental/climatic conditions (e.g., heat, humidity, and wind) in order to prevent heat illnesses, as well as preventing respiratory tract and infection problems (Edouard et al., 2019a).

EDUCATION

Athletes should be at the center of the illness and injury prevention. However, all stakeholders can positively impact and help implement prevention measures. Athletes, coaches and other members of the team need to be aware of the benefits of preventing injuries and illnesses, and to have an understanding of existing preventive measures. Preventative interventions are not likely to succeed without high levels of understanding and compliance. Medical teams, physiotherapists, psychologists, and dieticians should actively participate in the education of athletes and their entourage, as well as the governing bodies at international or national level, aiding the dissemination and promotion of preventative measures. Visual information is far more likely to be remembered than plain text. We advocate asking athletes in what format (for example oral presentation, infographics, and video) they would like to receive information. Communication between all stakeholders should be actively promoted.

VIGILANCE OF PAIN SYMPTOMS AND SUBCLINICAL ILLNESS MARKERS

Pain is a natural mechanism to protect against injuries (Tesarz et al., 2012), alerting us to actual, potential or imminent tissue damage (Moseley, 2016; Hainline et al., 2017). In sport, pain is a frequent complaint by the athletes, not always associated with injury/illness (Harringe et al., 2004; Bahr, 2009). Pain can be experienced as a physiological response to normal training (i.e., adaptation of tissues to exercises without any significant tissue damage), or as a physiological "warning signal" of a tissue damage (i.e., injury). Therefore, difficulties arise in the differentiation between "physiological" and "pathological" pain: "to distinguish the 'warning signal' from the 'noise' of pain" (Edouard, 2018). When athletes experience pain, they can choose to act protecting his/her body or choose to ignore the pain signal and continue with the sporting activities, hoping that the pain goes way.

We think that paying attention to the pain warning signal occurring during/as a consequence of sporting can help athletes prevent injuries. A functional diagnosis based on the level of pain and consequent level of impairment could be helpful for athletes, coaches, and health professionals to prevent tissue damages and injuries, without having a clear diagnosis. This enables load management strategies to attenuate or prevent increases in pain, with the aim of limiting tissue damage (Edouard, 2018). This is highly challenging in the context of elite/professional athletes given the need for high training loads. Nevertheless, we suggest being vigilant to pain, and not ignoring it.

Non-specific symptoms such as fatigue, myalgia or arthralgia, headache, and fever should be considered as warning signal of acute illness, but can also be symptomatic of over-reaching and overtraining (Schwellnus et al., 2016), and thus should not be ignored in a prevention strategy.

AVOID INFECTION RISK

Thirty percentage of illnesses reported during international athletics championships were claimed to be caused by infections (Edouard et al., 2019b), and 46–76% during Summer Olympic Games (Engebretsen et al., 2013; Soligard et al., 2017). Consequently, promoting measures to reduce the spread of communicable infections is highly relevant in the context of international championships. This includes basic actions such as (Hanstad et al., 2011; Alonso et al., 2012; Schwellnus et al., 2016, 2017; Timpka et al., 2017; Edouard et al., 2019a,b):

- washing hands, especially before eating and after going to the toilet (https://www.cdc.gov/handwashing/),
- avoiding hand shaking,
- keeping people that are unwell at a distance, for example separating sick athletes from the healthy athletes by requesting that competition organizers book extra hotel rooms,
- consuming safe food and water (i.e., avoid undercooked meat, wash and peel fruit where needed, use bottled water for drinking and cleaning teeth where water is not deemed drinkable),
- promoting food rich in vitamins and minerals (e.g., fruits and vegetables),
- promoting good sleep,
- being up to date with standard and travel vaccinations (https://www.nhs.uk/conditions/vaccinations/),
- checking your health status with your doctor.

TRAIN APPROPRIATELY AND OPTIMALLY

Optimal preparation for competition is fundamental to good performance and reducing the likelihood of injuries and illness (Schwellnus et al., 2016; Soligard et al., 2016). An appropriate training regime in athletics should include (Edouard et al., 2015a; Schwellnus et al., 2016; Soligard et al., 2016):

- physical and functional conditioning to improve sensorimotor control, by for instance stretching, muscular strengthening, particularly eccentric, proprioceptive, balance, increased resistance to fatigue,
- technical work to avoid technical mistakes that may result in injury,
- psychological work by for instance mental preparation, mental imagery, psychological input, etc. not forgetting optimal load management.

To our knowledge, no physical conditioning programmes have proven efficacy to decrease injuries in athletics, although examples exist in other sports (Lauersen et al., 2014). Some programmes have been proposed in athletics: eccentric exercises targeting the hamstrings (Malliaropoulos et al., 2012; Askling et al., 2014), "Decathlon of Injury Prevention" (by the Medical Commission of the French Athletics Federation: http://www.athle.fr/asp.net/main.html/html.aspx?htmlid=4175). The improvement of technical movements, as in the highly technical disciplines (e.g., pole vault and hurdles) seems of interest to prevent injuries (Rebella et al., 2008; Rebella, 2015). In this respect, efforts should be made to develop and validate injury prevention programmes (Edouard et al., 2015a).

HEALTH STATUS

When an athlete has a chronic disease (e.g., diabetes and epilepsy), it should be stabilized before the championships, alongside a management strategy for anticipated complications.

A history of previous injury has often associated with the occurrence of a new injury in sport (Hägglund et al., 2006). During major athletics championships, athletes who reported an injury complaint during the month before the championship had a 2- to 4-fold risk of sustaining a new injury during the period of the championship (Alonso et al., 2015; Timpka et al., 2017). Illness symptoms causing anxiety in the month before championships were associated with a 5-fold increase in the likelihood of in-championship injury (Timpka et al., 2017). As a basic practical application of such finding, we suggest that athletes, coaches, and medical teams should:

- improve rehabilitation procedure and general physical conditioning,
- continue regular conditioning after healing,
- be vigilant of recurring symptoms (i.e., attentive to pain, complaints, fatigue…),
- carefully follow athletes in final preparation of championships by for instance monitoring the athletes' health status before championships using a pre-participation health questionnaire (Alonso et al., 2015; Edouard et al., 2015c, 2018; Timpka et al., 2017).

Finally, to maintain good health status and include experience of previous health problems, we suggest optimal communication between athletes and the medical team, as well as other stakeholders around the athlete (e.g., coach, physical trainer, manager and club director, sports federation, agent/manager, family...), ensuring that medical confidentiality is maintained (Dijkstra et al., 2014; International Olympic Committee, 2016; Schwellnus et al., 2016). This can be summarized as "medical teams should know their athletes."

LIFESTYLE

A healthy lifestyle can help to prevent injuries and illnesses, including (Hirshkowitz et al., 2015; Irwin, 2015; Schwellnus et al., 2016; Walsh, 2018):

- good quality and quantity of sleep;
- regular hydration of safe water (i.e., closed bottle);
- appropriate nutrition with safe food, cooked meat, regular fruits and vegetables, wash fruit;
- improve recovery strategies;
- reducing life stress;
- avoid tobacco, excess alcohol, doping, and recreational drugs. . . .

ENVIRONMENTAL

Temperature, humidity, pollution, or altitude can influence sport performance and health.

Major Athletics championships often take place during the summer, consequently athletes may have to exercise in the heat, exposing the athlete to an increased risk of heat illness (Alonso et al., 2012; Périard et al., 2017; Timpka et al., 2017; Edouard et al., 2019b). As prevention measure, in a guideline for athletes and their entourage to prepare the IAAF World Athletics Championships Doha 2019 and the 2020 Tokyo Olympic Games, Racinais et al. suggest preparing heat acclimatization,

TABLE 1 | PREVATHLES: ten tips to hurdle the injuries and illnesses during major athletics championships.

Prepare the travel
Respect athlete characteristics and discipline specificity
Education
Vigilant of pain symptoms and subclinical illness markers
Avoid infection risk
Train appropriately and optimally
Health status
Lifestyle
Environmental
Safety

avoid dehydration, and adapt pre- and pre-cooling (Beat the Heat: https://www.iaaf.org/about-iaaf/documents/health-science).

In contrast, there is also evidence of cold extremes being linked to increased incidence of infection, with human rhinovirus thought to replicate more robustly in cooler nasal temperatures (Foxman et al., 2016).

Pollution could be a source of problems, especially in endurance disciplines where it has been linked to reduced sport performance and increase health problems (Rundell, 2012). To

FIGURE 1 | Infographic: ten tips to hurdle the injuries and illnesses during major athletics championships.

prevent illnesses due to pollution, prioritizing training far from vehicle pollution, and having a clear plan to manage poor air quality should it occur.

Major athletics events are rarely at high altitude, but athletes should prepare for the championships by training at the same altitude, adapting dietary strategies and with optimal psychological approach, alongside early arrival for acclimatization purposes (Burtscher et al., 2018).

SAFETY

The last tip is to advise athletes to follow safe athletics practice, but also safe habits in their daily life (e.g., driving, food, or sexual habits) (Schwellnus et al., 2016, 2017).

For sport practice, we suggest using appropriate equipment, for example throwing cage and jumping mat should not be too small and should be in perfect condition in order to ensure security when athletes throw or jump. We suggest that the competition schedules should be appropriate to the circadian rhythm (e.g., not during the night) and to the weather conditions (e.g., not during, e.g., extreme heat, rain, storm….). To avoid accident with throws, we suggest avoiding the occurrence of two events at the same location (Edouard et al., 2015a). The medical services at competitions should be appropriately organized for the level of competition and can contribute to illness and injury prevention strategy (Pendergraph et al., 2005; Zemper, 2005; Edouard et al., under revision).

CONCLUSIONS

These ten tips are based on our field experience, and the evidence from epidemiological and/or experimental studies on athletics, together with extrapolations of studies in other sports. Their efficacy to prevent the occurrence of new injury and illness should be analyzed in order to promote their use. But before that, with sound judgement from basic and logical practice, and given the low risk in the benefit/risk balance, we suggest athletes and their entourage using these ten tips "PREVATHLES" (**Table 1**, **Figure 1**, and **Supplementary Video 1**) to try to limit the risk of injury and illness during championships. We hope these tips will help improve and optimize health protection and injury/illness prevention in athletes of all levels and have a subsequent benefit to overall competition performance. Efforts must be continued to progress in athletics injury and illness prevention!

AUTHOR CONTRIBUTIONS

PE conceived and designed the manuscript. PE, AR, and AM drafted the manuscript. DG identified the framework and produced the infographic. PE and AM commented on the infographic drafts and video drafts. JD identified the framework and produced the video. PE, AR, AM, JD, DG, MK, FD, and PB edited, critically revised the manuscript, and approved the final version.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2019.00012/full#supplementary-material

Supplementary Video 1 | PREVATHLES: ten tips to hurdle the injuries and illnesses during major athletics championships.

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ORIGINAL RESEARCH
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Lane and Heat Draw Have Little Effect on Placings and Progression in Olympic and IAAF World Championship 800 m Running

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The aim of this study was to establish whether the lane and heat draw influenced placings and progression in world-class 800-m track running. Finishing positions and times of 1,086 performances at the Olympic Games and IAAF World Championships between 1999 and 2017 were obtained. Mean finishing and season's best times (SB), as well as placings and progression rates, were found for each heat number and for the inner (Lanes 1 and 2), middle (Lanes 3–6), and outer lanes (Lanes 7 and 8). In the qualifying heats and semi-finals, the theoretically expected number of fastest losers (non-automatic qualifiers) per heat was compared with the actual number. One-way ANOVA with Bonferroni *post-hoc* tests were conducted to compare finishing times between lane and heat numbers across rounds. With regard to the order of heats, there were no differences between finishing times in either the qualifying heats or semi-final rounds for men; in the women's event, only Semi-final 3 was the quickest, but still did not have higher progression rates. SB times did not differ between heats within each round, highlighting the fair distribution of athletes. Progression rates for each lane during the qualifying heats ranged between 36 and 52% (men) and between 49 and 61% (women), close to the expected ranges of 45 and 55%, respectively. The middle lanes were quicker in the seeded semi-finals and finals only. Men in the outer lanes fared slightly worse and should focus on achieving the optimal tactical position after breaking from lanes. The IAAF could reconsider how they allocate seeded lanes in the later rounds by switching the fifth and sixth fastest athletes from the outer to the inner lanes. Regarding the heat draw, athletes mostly did not take advantage of knowing previous performances from earlier races, and probably focused on achieving an automatic qualifying position instead. However, the fastest losers in the women's last semi-final were faster and showed that benefitting from the heat draw is possible with tactical coaching.

Keywords: coaching, elite-standard athletes, endurance, race tactics, track and field

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INTRODUCTION

The 800 m is the shortest middle-distance event held at the Olympic Games and International Association of Athletics Federations (IAAF) World Championships, and differs from other distance races in that the first bend is run in lanes (IAAF, 2017a). Recent research has shown that very fast starting paces are adopted in global championship 800 m races (Hanley et al., 2019), and the effects of lane allocation for the first bend could be a factor affecting this. The lane allocated to each athlete in the semi-finals and final is based on performances achieved over the course of the year (including performances in earlier rounds of those championships) so that the four athletes with the fastest times are randomly drawn in the middle four lanes, with the next two fastest randomly drawn in Lanes 7 and 8, and the two slowest randomly drawn in Lanes 1 and 2 (IAAF, 2017a); the four slowest were randomly drawn across Lanes 1, 2, 7, and 8 until 2009 (IAAF, 1997, 2008).

Unlike the semi-finals and final, in the first round (the "qualifying heats"), the lane draw is by lot, and could therefore confer an advantage on those drawn in the middle four lanes as previous research suggests running speed is more limited in the inner lanes because of constraints on the forces generated by the inside leg (Taboga et al., 2016). Indeed, the IAAF discontinued indoor 200 m races in 2005 (that are held on six-lane 200-m tracks) because those allocated to the outer lanes had too great an advantage (Taboga et al., 2016). Additionally, the very outer lanes on an outdoor track (lanes 7 and 8) are considered disadvantageous because athletes starting in those lanes cannot easily see other athletes to pace themselves in the very early stages (Morgan, 2016). Although the proportion of the race run in lanes is relatively short, the need to break from lanes on the back straight means that deciding on the best route to the 200-m distance, where the next bend occurs, is highly important because athletes want to minimize total distance run, avoid being blocked in, and gain possible drafting benefits (Casado and Renfree, 2018). In 800 m championship racing, athletes can improve their chances of a middle lane draw by running a season's best time in the previous round(s), but no study to date has examined what effect lane draw has on placings and progression in 800 m running in terms of qualifying for later rounds or winning medals in world-class competition. New research comparing placings and progression and finishing times for the inner, middle, and outer lanes will therefore highlight whether such an advantage does exist, and therefore provide information that could be used by the IAAF to consider the fairness of the current allocation rules.

In many sports that adopt head-to-head competition structures (e.g., swimming and rowing; FINA, 2017; FISA, 2017), athletes are seeded before the competition begins to try to ensure that the best athletes reach the final. Such an approach is also taken in 800 m running, where the heat draw (i.e., which heat each athlete runs in) is based on performances achieved during the qualification period, with athletes allocated in a zigzag distribution (**Table 1**). This distribution of athletes is intended to achieve parity across heats, although exceptions are sometimes made when drawing heats to separate athletes from the same nation (IAAF, 2017a). Seeding in the semi-finals and final is based on these same performances, except for those athletes who run faster during the earlier rounds (as for the lane draw). Progress from the qualifying heats to the semi-finals, and from the semi-finals to the final, can be achieved either through a high-enough finishing position (usually the top two) or by having one of the best non-automatic qualifying finishing times; athletes qualifying by time rather than position are often referred

TABLE 1 | Example of how 48 athletes would be drawn into six qualifying heats.

Heat allocation	Athlete ranking by SB							
A	1	12	13	24	25	36	37	48
B	2	11	14	23	26	35	38	47
C	3	10	15	22	27	34	39	46
D	4	9	16	21	28	33	40	45
E	5	8	17	20	29	32	41	44
F	6	7	18	19	30	31	42	43

Athletes are placed in qualifying heats (and semi-finals) using the order of seeding by season's best times (SB) in a zigzag distribution (IAAF, 2017a), so that the mean ranking per heat is equal. The allocation can deviate from this model if athletes representing the same nation are drawn in a heat together. The actual order in which the heats are run is drawn by lots.

to as "fastest losers" (IAAF, 2017b). Very occasionally, athletes who fail to qualify can progress if the Jury of Appeal decides they have been impeded unfairly (IAAF, 2017a). Knowing the finishing times of other athletes in earlier heats could give those in the last heat a competitive advantage (IAAF, 2017a) as they could theoretically pace themselves to achieve the required time and qualify as fastest losers (provided not too many rivals in the same race run faster times). However, as with the lane draw, whether the last heat does in fact produce the greatest proportion of fastest losers has not been examined, and therefore it is not established whether heat draw has any effect on placings and progression in qualifying (i.e., for the fastest loser positions). It has also not been ascertained whether seeding for lanes (in the first qualifying round) or heats produces equally weighted races in global championships, and therefore whether the process of allocating athletes by qualifying time works in achieving fair competition. Knowing whether there are differences between lanes or heats could inform coaches and athletes of suitable tactics to adopt to take advantage of the draw, or minimize any potential drawbacks. Similarly, if the draw is potentially unfair, the IAAF could reconsider the processes adopted for allocating heats and lanes. The aim of this study was to establish whether the draws for heats and lanes have an effect on success in 800 m racing. It was hypothesized that athletes running in the middle four lanes would achieve better placings and progression in the seeded semi-finals and finals, but that there would be no difference for placings or progression in the unseeded qualifying heats, or between the randomly allocated heat numbers in the qualifying heats and semi-finals.

MATERIALS AND METHODS

Research Approval

The protocol was approved by the Carnegie School of Sport Research Ethics Committee with the requirement for informed consent waived as the study analyzed publicly available data only. The study was conducted in accordance with the recognized ethical standards of the Declaration of Helsinki.

Participants

Official electronic finishing times and positions of all competitors in the men's and women's 800 m competitions at the Olympic

Games and IAAF World Championships between 1999 and 2017 were obtained from the open-access IAAF website (IAAF, 2018) as shown in **Supplementary Data**. In each of the championships analyzed, a round of qualifying heats was held, with the number of qualifying heats varying depending on the number of entrants. Three semi-finals were normally held for each 800 m event (men and women), but because only two semi-finals were held in a small number of championships (i.e., 1999, 2000, and 2013 for women; 2001 for both men and women), these championships were omitted. A total of 1086 championship performances (303 men: 664 performances; 206 women: 422 performances), with many athletes competing in several championships, were analyzed. The performances of 61 men and 52 women in the qualifying heats, and 14 men and six women in the semi-finals, were removed as outliers as their finishing times were more than 1.5 times the interquartile range (IQR) from the median of the scores (Hanley, 2016). The results of 13 men and three women who were disqualified, and eight men and four women who did not finish during the qualifying heats, were excluded from the analysis. In the semi-finals, the results of five men and five women who did not finish, and four men who were disqualified, were not included in the analysis of that round. The results of three men and one woman who qualified for the semi-finals via the Jury of Appeal were included for analysis in the semi-finals and final (as appropriate), but not in the qualifying heats. Similarly, the results of two men who qualified for the final (in 2009) by appeal were included for analysis in the qualifying heats and final. The season's best time (SB) for each analyzed athlete was obtained from the IAAF website (IAAF, 2018), and their finishing times for each round calculated as a percentage of SB ("SB%"). Sixteen men and five women who were analyzed had no SB recorded before the championships.

Data Analysis

The study was designed as observational research in describing placings and progression per ordered lane and heat. In most championships, the stadium had an eight-lane track; on those occasions when the track had nine lanes, the inside lane was typically vacated and thus for those occasions Lane 2 was considered Lane 1, etc. On the very rare occasions that nine athletes competed in a race and doubling-up in a single lane occurred, both athletes' performances were counted for that lane. For the analysis of effect of lane draw, the number of qualifiers from each lane (comprising automatic qualifiers and fastest losers, but not those who progressed by appeal) in the qualifying heats and semi-finals were measured, as were the number of medalists per lane in the final.

The number of qualifying heats per championship varied from six to nine (men) and five to eight (women). Accordingly, the number of athletes qualifying as fastest losers varied so that, when added to the automatic qualifiers, 24 progressed to the semi-finals. Exceptions occurred in the men's event in 2000, 2001, and 2012 when appeals meant that 25 took part in the semi-finals, and 2017, when one athlete dropped out of the competition before the semi-finals. The single exception in the women's events was in 2009 when 25 took part in the semi-finals because one athlete progressed by appeal. To account for the variance in the number of qualifying heats, the theoretically "expected" number of fastest losers per heat was calculated; for example, if there were eight fastest losers qualifying from eight qualifying heats, the expected number per heat was one. The expected total across all championships for each qualifying heat was then found (i.e., Heat 1, Heat 2, etc.) and compared with the actual number of qualifiers from those heats. All semi-finals had a format of three separate races, with the top two finishers advancing as automatic qualifiers and two fastest losers qualifying across all three races. Because there was a set number of automatic qualifiers per qualifying heat and semi-final, the performances of the fastest losers were analyzed rather than the automatic qualifiers, but the mean times of all athletes in each heat were also measured to indicate overall race quality, and to allow comparisons between heats regarding whether even distribution of athlete ability occurred.

Statistics

Results are reported as mean ± one standard deviation (SD). One-way analysis of variance (ANOVA) with Bonferroni *post-hoc* tests were conducted to compare mean finishing and season's best times between qualifying heat numbers and semi-final numbers for both fastest losers and all athletes. One-way ANOVA with Bonferroni *post-hoc* tests were also used to compare finishing times, SBs and SB% between the "inner" lanes (Lanes 1 and 2), "middle" lanes (Lanes 3, 4, 5, and 6), and "outer" lanes (Lanes 7 and 8). Effect sizes for differences found were calculated using Cohen's d (Cohen, 1988), rounded to two decimal places and considered to be either trivial ($d < 0.20$), small (0.21–0.60), moderate (0.61–1.20), large (1.21–2.00), or very large (> 2.01) (Hopkins et al., 2009). Pearson's chi-squared test of association (χ^2) compared observed counts of categorical data (e.g., qualified or did not qualify, won a medal, or did not) between the inner, middle, and outer lanes. Similarly, to analyze progression rates from qualifying heats, the number of fastest losers from the first half of the qualifying heats were grouped, and compared with the number from the second half using Pearson's chi-squared test of association. Progression rates in the qualifying heats were compared using the first and second halves of the draw because of the disparity in the number of qualifying heats between championships (e.g., Heat 5 in 2004 was the middle heat of nine, whereas in 2005 it was the second last heat). In those instances where an odd number of qualifying heats were held (as occurred in four men's and three women's championships), there was one qualifying heat more included in the first half than in the second. An alpha level of 5% was used for all tests; 95% confidence intervals (95% CI) were also calculated (for the chi-squared test, this was the 95% CI of the unadjusted odds ratio; Field, 2009).

RESULTS

Figure 1 shows the placings and progression for each lane based on the proportion of athletes running in that lane who qualified for the next round, or who won medals in the final, compared with the expected rate per lane (which equaled the mean of the actual rates found across all lanes). During the qualifying heats, there were no differences in the women's event between the

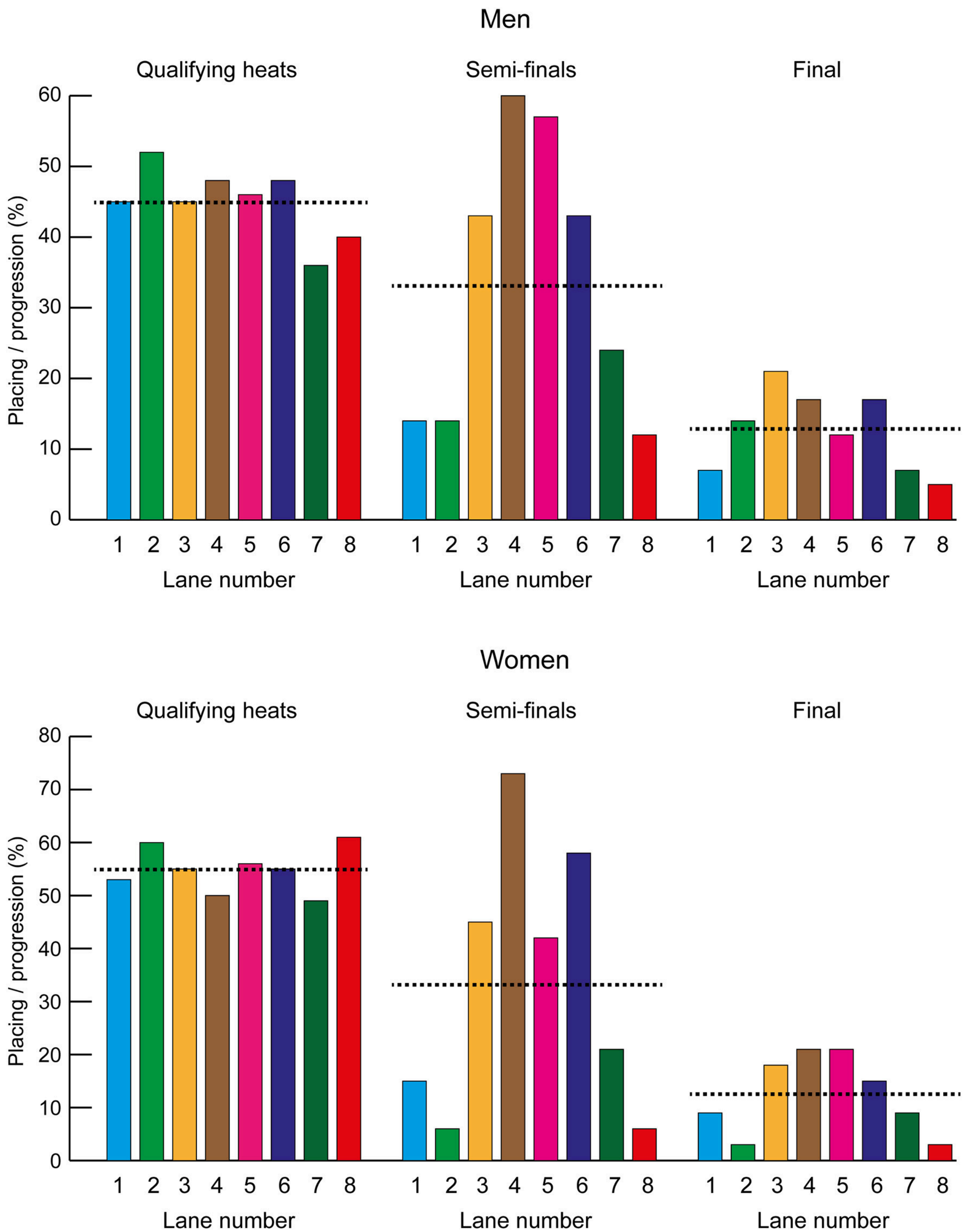

FIGURE 1 | Placings and progression rates (%) for each lane based on the proportion of athletes running in that lane who qualified for the next round, or who won medals in the final. The expected value (shown as a dotted line) refers to the percentage of athletes who would be expected to qualify from each lane or win a medal if randomly allocated.

progression rates of those running in the middle lanes compared with either the inner or outer lanes, but in the men's qualifying heats the progression rate was higher in the middle lanes and inner lanes than in the outer lanes [middle vs. outer: $\chi^2_{(1)} = 4.00$, $p = 0.045$, 95% CI: 1.01–2.04; inner vs. outer: $\chi^2_{(1)} = 4.09$, $p = 0.043$, 95% CI: 1.01–2.35]. In the men's semi-finals, those

TABLE 2 | The mean finishing and SB times (min:s) (±SD) for the inner (Lanes 1 and 2), middle (Lanes 3–6) and outer lanes (Lanes 7 and 8) in each round.

	Men			Women		
	Inner	**Middle**	**Outer**	**Inner**	**Middle**	**Outer**
Finishing time (min:s)						
Qualifying heats	1:47.32 (±1.29)	1:47.39 (±1.43)	1:47.48 (±1.23)	2:02.17 (±1.93)	2:02.47 (±2.47)	2:02.28 (±2.18)
Semi-finals	1:46.58[a] (±1.01)	1:45.66[ab] (±1.16)	1:46.55[b] (±1.23)	2:00.87[a] (±1.36)	1:59.54[ab] (±1.35)	2:00.65[b] (±1.53)
Final	1:45.33 (±1.24)	1:44.92[b] (±1.44)	1:45.89[b] (±1.69)	1:59.04[a] (±1.21)	1:57.68[ab] (±1.77)	1:59.05[b] (±1.75)
Season's best time (min:s)						
Qualifying heats	1:45.47 (±1.22)	1:45.57 (±1.65)	1:45.66 (±1.65)	2:00.17 (±1.61)	2:00.14 (±2.29)	2:00.03 (±1.64)
Semi-finals	1:45.69[ac] (±0.63)	1:44.09[ab] (±0.66)	1:45.27[bc] (±0.82)	2:00.37[ac] (±0.74)	1:58.31[ab] (±1.17)	1:59.86[bc] (±0.63)
Final	1:44.71[a] (±0.62)	1:43.64[ab] (±0.67)	1:44.38[b] (±0.45)	1:58.65[a] (±0.54)	1:57.08[ab] (±1.00)	1:58.46[b] (±0.82)

[a] *Significant difference between middle and inner lanes.*
[b] *Significant difference between middle and outer lanes.*
[c] *Significant difference between inner and outer lanes.*
Significant differences ($p < 0.05$) between running times have been annotated only when the effect size was moderate or larger ($d \geq 0.61$) and the 95% CI did not cross zero.

in the middle lanes were more likely to qualify [middle vs. inner lanes: $\chi^2_{(1)} = 31.77$, $p < 0.001$, 95% CI: 3.15–12.31; middle vs. outer lanes: $\chi^2_{(1)} = 24.52$, $p < 0.001$, 95% CI: 2.46–8.77], as was the case in the women's semi-finals [middle vs. inner lanes: $\chi^2_{(1)} = 35.43$, $p < 0.001$, 95% CI: 4.30–23.79; middle vs. outer lanes: $\chi^2_{(1)} = 31.12$, $p < 0.001$, 95% CI: 3.54–16.89]. In the men's finals, those in the middle lanes were more likely to win a medal than those in the outer lanes [men: $\chi^2_{(1)} = 5.65$, $p = 0.017$, 95% CI: 1.17–8.51], but not more so than those in the inner lanes. In the women's finals, those in the middle lanes were more likely to win a medal than those in either the inner or outer lanes [both: $\chi^2_{(1)} = 5.84$, $p = 0.016$, 95% CI: 1.20–10.89].

Table 2 shows the mean finishing and SB times for those running in the inner, middle, and outer lanes, with annotations of any differences found. In all tables and the text below, differences between running times have been annotated only when the effect size was moderate or larger and the 95% CI did not cross zero. There were no differences found between inner, middle and outer lanes for SB% in any round for women and, in the men's event, only between those in the middle lanes (101.5 ± 1.2%) and inner lanes (100.8 ± 1.1%) in the semi-finals ($p < 0.001$, $d = 0.62$, 95% CI: 0.28–1.05).

Tables 3, **4** show the progression of the fastest losers by qualifying heat and semi-finals, as well as the mean times run by the fastest losers and all athletes in each ordered heat. In both men's and women's qualifying heats, there was no difference in qualifying progression rates between the first half and second half of races. In the men's event, there were no differences between mean finishing times in either the qualifying heats or semi-finals for either fastest losers or all athletes, although men competing in Semi-final 1 were more likely to qualify as fastest losers than those in Semi-final 3 [$\chi^2_{(1)} = 5.87$, $p = 0.015$, 95% CI: 1.21–10.45]. In the women's event, there were no differences in the qualifying heats, but Semi-final 3 was quicker than both Semi-final 1 ($p = 0.028$, $d = 1.79$, 95% CI: 0.09–1.92) and Semi-final 2 ($p = 0.017$, $d = 1.40$, 95% CI: 0.15–1.74); however, no differences were found regarding likelihood of qualifying as fastest losers.

TABLE 3 | Progression of fastest losers by qualifying heat and semi-final in the men's event; the number of qualifiers (as fastest losers) is shown alongside the expected number from that heat number ("exp.").

Heat	Occurrences	Qualifiers (exp.)	Fastest losers (min:s)	All athletes (min:s)
Heats				
1	14	7 (12)	1:46.62 (±0.69)	1:47.44 (±1.33)
2	14	13 (12)	1:46.40 (±0.47)	1:47.22 (±1.17)
3	14	17 (12)	1:46.28 (±0.35)	1:47.18 (±1.66)
4	14	13 (12)	1:46.12 (±0.53)	1:47.25 (±1.22)
5	14	14 (12)	1:46.53 (±0.45)	1:47.51 (±1.39)
6	14	6 (12)	1:46.45 (±0.61)	1:47.78 (±1.38)
7	8	7 (6)	1:46.67 (±0.34)	1:47.42 (±1.20)
8	5	6 (5)	1:46.07 (±0.26)	1:47.35 (±1.33)
9	1	0 (1)	–	1:47.57 (±0.78)
Semi-finals				
1	14	14 (9)	1:44.92 (±0.50)	1:46.00 (±1.21)
2	14	9 (9)	1:45.12 (±0.35)	1:46.09 (±1.13)
3	14	5 (9)	1:45.38 (±0.35)	1:46.23 (±1.32)

The mean times (±SD) for the fastest losers, as well as all athletes in each heat, are also shown. All expected values were rounded to the nearest integer.

The mean SBs for the fastest losers and all athletes per heat are shown in **Table 5**. There were no differences found between SBs in either the qualifying heats or semi-finals for either men or women.

DISCUSSION

The aim of this study was to establish whether the draws for heats and lanes have an effect on placings and progression in 800 m championship racing. The fact that lane draw (in the qualifying heats) and heat draw (qualifying heats and semi-finals) is by lot, with no differences in SBs found, allows for a robust analysis of the effects of those draws. Regarding the lane draw, there was no difference in qualification rates or

TABLE 4 | Progression of fastest losers by qualifying heat and semi-final in the women's races; the number of qualifiers (as fastest losers) is shown alongside the expected number from that heat number ("exp.").

Heat	Occurrences	Qualifiers (exp.)	Fastest losers (min:s)	All athletes (min:s)
Heats				
1	11	9 (12)	2:01.18 (±0.82)	2:02.22 (±1.87)
2	11	14 (12)	2:01.24 (±1.10)	2:02.20 (±2.21)
3	11	7 (12)	2:01.43 (±1.51)	2:03.07 (±2.74)
4	11	11 (12)	2:01.10 (±1.69)	2:02.15 (±2.08)
5	11	13 (12)	2:01.07 (±0.69)	2:02.72 (±2.57)
6	8	13 (9)	2:01.24 (±1.16)	2:01.78 (±2.13)
7	1	0 (1)	–	2:02.49 (±0.90)
8	1	0 (1)	–	2:01.23 (±1.89)
Semi-finals				
1	11	5 (7)	1:59.27 (±0.37)	2:00.13 (±1.30)
2	11	8 (7)	1:59.21 (±0.71)	1:59.91 (±1.30)
3	11	9 (7)	1:58.26 (±0.64)	2:00.41 (±1.89)

The mean times (±SD) for the fastest losers, as well as all athletes in each heat, are also shown. All expected values were rounded to the nearest integer.

TABLE 5 | The mean SB times (min:s) (±SD) for the fastest losers, as well as all athletes, in each heat.

Heat	Fastest losers (min:s)	All athletes (min:s)	Fastest losers (min:s)	All athletes (min:s)
	Men		Women	
Qualifying heats				
1	1:46.56 (±3.07)	1:45.68 (±1.90)	1:59.86 (±1.08)	2:00.20 (±1.99)
2	1:45.27 (±0.95)	1:45.51 (±1.53)	1:59.43 (±1.07)	1:59.95 (±1.99)
3	1:45.88 (±1.30)	1:45.55 (±1.63)	1:59.84 (±0.87)	2:00.12 (±2.20)
4	1:45.26 (±1.22)	1:45.51 (±1.43)	2:00.43 (±1.28)	2:00.03 (±1.84)
5	1:45.32 (±1.39)	1:45.53 (±1.50)	2:00.28 (±1.23)	2:00.07 (±1.52)
6	1:45.67 (±1.38)	1:45.58 (±1.48)	2:00.45 (±0.79)	2:00.27 (±2.41)
7	1:45.65 (±1.20)	1:45.67 (±1.60)	–	2:01.33 (±2.97)
8	1:45.94 (±1.33)	1:45.60 (±1.33)	–	1:59.93 (±1.88)
9	–	1:45.57 (±1.35)	–	–
Semi-finals				
1	1:44.68 (±0.94)	1:44.81 (±0.94)	1:59.08 (±0.85)	1:59.23 (±1.23)
2	1:44.38 (±0.95)	1:44.73 (±1.06)	1:58.48 (±1.14)	1:59.18 (±1.44)
3	1:44.46 (±0.68)	1:44.81 (±0.99)	1:58.43 (±1.30)	1:59.23 (±1.32)

finishing times between the inner, middle and outer lanes during the randomly drawn first-round qualifying heats for women, although men in the outer lanes had lower progression rates than those in the inner and middle lanes (by ∼10%). This was despite no difference in finishing times, SBs or SB% between lane groupings, and suggests that some men were unable to overcome the disadvantages of running in the outer lanes, and so the hypothesis that there would be no difference between lanes for placings or progression in the unseeded qualifying heats was rejected for the men's event. The lack of a difference in finishing times could reflect how achieving qualification can be a matter of very close finishes (Hanley et al., 2019), and tiny details of pacing can matter. As hypothesized, there were higher placings and progression rates for the middle four lanes during the semi-finals and final, which was unsurprising as the effects are biased because the highest-ranked athletes were drawn in those lanes, and their SBs were indeed faster than those in the inner and outer lanes. Apart from one exception, there were no differences in SB% between lane groupings, showing that athletes ran times relative to their ability regardless of their allocated lane.

Starting in the outer lanes prevents athletes from seeing their rivals who could be used as external references for pacing (Renfree et al., 2014a), but also allows them to choose a better position when breaking as there are few if any opponents on their outside. Conversely, running in the inner positions allows athletes to see their opponents but might be blocked by them as they converge inwards after the breaking point, although the inner lanes were slower than the outer lanes during the semi-finals only (which was not unexpected as the outer lanes have been allocated to faster athletes since 2009). Each lane thus has its own advantages and disadvantages, and though the random allocation of lanes that occurs in the qualifying heats is fair, being able to see other competitors in the inner lanes might outweigh the disadvantage of the tighter bend for men. Furthermore, no differences were found in the probability of achieving a medal during the men's finals between athletes in the inner and middle lanes, even though the middle lane athletes had run faster SBs. The concern that running in the inner lanes might hinder 800 m athletes is therefore unjustified as athletes run the other three bends in the inner lanes to achieve the shortest total distance in any case, and are therefore accustomed to their curvature. Additionally, the slower pace adopted compared with 200 and 400 m races might reduce any impact of running in the inner lanes. It is possible that those athletes who doubled up in a lane competed with each other for the inside position within their lane, necessitating a faster start than normal, but these incidences were very rare. Instead, the very inside lane was often vacated, either because fewer than eight athletes competed in any particular race (although never in the semi-finals) or because a nine-lane track was used.

Because the first 100 m, which is run in lanes, represents one eighth of the total race distance, tactical positioning is a very important aspect of championship racing (Casado and Renfree, 2018), and athletes should consider potential tactical options. Whereas world-class athletes drawn in the outer lanes during the heats do not need to worry unduly about their starting lane, as, like in the later rounds, it is usually those with the fastest season's best times who qualify (Renfree et al., 2014b), those of lesser ability need to reduce any potential disadvantage of starting in the outer lanes. These athletes should try to experience multiple races before a major championship, as practicing running in the outer lanes can be useful when learning to take the shortest realistic path when breaking to the inside (Martin and Coe, 1997). Championship racing is, however, quite different from Diamond League competition because of the absence of pacemakers (Filipas et al., 2018) and athletes should develop tactical judgment when breaking to avoid being boxed in. Athletes might break for the inside earlier on the back straight when a headwind is blowing because of possible drafting benefits (Casado and Renfree, 2018), but those athletes in the very outer lanes should consider the extra distance run (Martin and Coe, 1997). Indeed, those men in the outer lanes (who were less likely to progress from the qualifying heats) might have made poor tactical decisions when breaking to the inside, resulting in more total distance run. Ultimately, athletes should focus on achieving the optimal tactical position at 200 and 400 m as this has a greater effect on qualifying probability (Casado and Renfree, 2018). Based on these novel results, the IAAF could reconsider the current performance-based allocation of lanes in 800 m outdoor championship events, with athletes ranked fifth and sixth randomly allocated to the inner lanes, rather than the outer lanes at present. In cases where athletes drop out of the competition after lanes have been drawn (e.g., before the semi-finals), athletes could be moved to fill empty lanes to move them closer together, especially to avoid isolating athletes in the outer lanes.

The draw for the qualifying heats and semi-finals is designed to achieve equally weighted races so that the highest ranked athletes avoid each other and qualify for the next round. This study found that the seeding of qualifying heats and semi-finals in this manner did indeed achieve a fair distribution of competitors' abilities as no differences were found for either all athletes or the fastest losers within a race; this part of our hypothesis was therefore accepted. Indeed, the mean times for fastest losers in the qualifying heats were within such a narrow range (1:46.07–1:46.67 for men and 2:01.07–2:01.43 for women) that they provide coaches with very strong indicators of typical 800 m performances needed to progress. Although, from a tactical viewpoint, it is considered advantageous to run in later heats (IAAF, 2017a), this study found that athletes did not take advantage of knowing what times previous fastest losers had run (the progression rate for men's Heat 6 was approximately half that of earlier qualifying heats), notwithstanding that those in qualifying Heat 1 had relatively poor progression rates, possibly because they had no previous heat times to base their pacing on. By contrast, it was noticeable in the men's event that half of all fastest losers in the semi-finals qualified from the first race, and on the one occasion that women had eight qualifying heats, no fastest losers qualified from the last two heats. There are a number of reasons why most athletes in the later races did not benefit from knowing the current fastest loser standings: first, they might not have known other athletes' times as the duration between races is relatively short, and athletes have to focus on their own race; second, it might be too difficult to pace oneself to such a specific time with few immediate sources of feedback; and third, middle-distance athletes have been found to be more concerned with finishing position, rather than time, even during the qualifying heats (Hanley and Hettinga, 2018). This makes sense given that, in the semi-finals, at least one third-placed athlete will not qualify, no matter how good their finishing time is, and reiterates the importance of achieving an optimal tactical position after breaking from lanes. This was supported by the finding that the fastest losers in the women's Semi-final 3 were faster than those in the prior semi-finals, but the numbers qualifying were not greater. It is also possible that athletes in the later heats calculate that they are unlikely to beat earlier fastest loser times, and focus on trying to achieve an automatic qualifying time. As with the lane draw, there were no clear benefits to being drawn in any particular heat (even if there potentially could be), and athletes should similarly not worry about this aspect of the championship structure at the expense of focusing on the race itself. The data used for this study were taken from championship results and, although this provides high ecological validity, are therefore limited to the numbers of participants who took part. Because the analysis undertaken involved dividing these athletes by heat and lane, the numbers available for statistical analysis are relatively low. As low sample sizes can lead to underpowered studies and a consequent increase in the possibility of Type II errors (Cohen, 1992), it is possible that differences occurred that were not detected. Future studies should consider adding to the data analyzed in this study with those found in future IAAF World Championships and Olympic Games.

CONCLUSIONS

This study analyzed men's and women's 800 m races at global athletics championships and found that there was little effect of lane or heat draw on eventual placings and progression, especially for women. In the randomly drawn qualifying heats, men in the outer lanes fared slightly worse, possibly because of greater difficulties in early pacing, and coaches should work with their athletes to practice pace management in the first 200 m in particular. Athletes should therefore adopt the most appropriate tactics when breaking from their lane (a balance between running the shortest distance, avoiding being boxed in, and obtaining possible drafting and pacing benefits from the pack). There was no clear evidence of athletes in later heats taking advantage of knowing other athletes' finishing times (e.g., more men qualified from the first semi-final than the last one, rather than the other way around), but this does not mean that this is not possible, and coaches could try to pass on useful information about approximate target times, or whether focusing on an automatic qualifying position is the priority. Seeding for the qualifying heats and semi-finals works in terms of distributing athletes evenly and fairly, but the IAAF could consider allocating the inner lanes to faster athletes rather than the outer lanes as the inner lanes appeared to present less of a disadvantage. It should be noted though that the analysis might be underpowered with an increased possibility of Type II errors, and hence future studies should consider adding to these data already recorded at global championships.

DATA AVAILABILITY

All datasets generated for this study are included in the manuscript/**Supplementary Files**.

AUTHOR CONTRIBUTIONS

BH, AC, and AR conceptualized and designed the study, wrote the manuscript, and read and approved the final manuscript. BH conducted the data collection and analyses and created tables. All authors read and approved the final manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2019.00019/full#supplementary-material

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The Location of the Center of Pressure on the Starting Block Is Related to Sprint Start Performance

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Force application locations [i.e., center of pressure (COP)] on the block surface are not necessarily the same for individuals even if the same block locations and angles are used. The purpose of this study was to examine the association of block clearance performance with COP location on the starting block surface. Twenty-one male sprinters performed 60 m sprints from the starting blocks, during which the ground reaction forces (GRFs) on the starting blocks were recorded using two force platforms. Using a previously validated method, changes in COP location on the block surface during the block clearance for each block was calculated from the marker coordinates on the block surface, GRF signals, and moment data around the center of the force platform at the ground level. Moreover, average horizontal external power (AHEP), which was considered the key performance criterion, was computed. Statistical parametric mapping (SPM) 1D linear regressions were used to test relationships between AHEP and COP location curves in the anteroposterior and vertical directions. The COP for both legs moved backward and upward (0.042 and 0.042 m for the front block and 0.030 and 0.034 m for the rear block) at first and then forward and downward (0.113 and 0.094 m for the front block and 0.095 and 0.087 m for the rear block) toward the toe-off. Based on SPM results, AHEP was correlated with front block anteroposterior and vertical COP locations from 12.9 to 20.8% and from 10.4 to 22.2% of the force production phase, respectively, while it was correlated with rear block vertical COP location from 31.9 to 37.4% of the force production phase. In conclusion, the current results demonstrate that, regardless of the starting block location and angle, better sprint start performance is accomplished with a higher and more to the rear COP on the starting block surface, when COP is located close to heel during the middle phase of the block clearance. The fact that the COP location is related to sprint start performance will be useful for sprinters and coaches who intend to improve sprint start performance.

Keywords: block clearance, GRF, running, acceleration, power, track and field

INTRODUCTION

Block clearance at the start of a race is important for the entire performance of a 100 m race (Mero, 1988; Bezodis et al., 2015; Willwacher et al., 2016). The magnitudes of net and propulsive GRFs at the block clearance are pivotal for a better sprint start performance (Rabita et al., 2015; Bezodis et al., 2019). To produce large net and propulsive GRFs during the sprint start, starting blocks are used for the start of sprint races.

The location and angle of each block can be arranged by a sprinter for accomplishing his/her best race performance. Because of these regulations, there have been studies which examined locations and angles of starting blocks for better start or entire sprint race performances (Dickinson, 1934; Kistler, 1934; Henry, 1952; Sigerseth and Grinaker, 1962; Stock, 1962; Guissard et al., 1992; Schot and Knutzen, 1992; Harland and Steele, 1997; Mero et al., 2006; Slawinski et al., 2012; Schrödter et al., 2016). For example, it has been found that longer anteroposterior inter-block spacing could result in greater block clearance velocity through greater propulsive impulse, if it was accompanied with longer push phase duration and vice versa (Dickinson, 1934; Kistler, 1934; Henry, 1952; Schot and Knutzen, 1992). Moreover, intermediate anteroposterior inter-block spacing was recommended for better block clearance performance (Sigerseth and Grinaker, 1962; Stock, 1962). For block angles, no effect of habitual block angle on block power was found (Schrödter et al., 2016), whereas the reduction of the front block angle resulted in an increment of block clearance velocity with consistent block clearance duration (Guissard et al., 1992; Mero et al., 2006).

Although the above-mentioned findings are useful for understanding determinants of the block clearance performance in terms of a block location and angle, actual force application locations [i.e., center of pressure (COP)] on the block surface are not necessarily the same for individuals even if the same block locations and angles are used. Thus, the COP location on the starting block surface during the block clearance would be a new interesting aspect of the performance indicator for block clearance. Moreover, such information will be beneficial for understanding better strategy of force application on the starting blocks. In addition, the location of COP on the starting block surface for better start performance will be useful for sprinters to manipulate the location of force application on the starting block during the block clearance. A method calculating COP location on the starting block surface has recently been proposed, and its accuracy has been confirmed (Ohshima et al., 2019). Typically, COP on the starting block moves backward and upward at first and then forward and downward until toe-off for both the front and rear legs (Ohshima et al., 2019). Using this new method, the actual COP location on the block surface for better performance can be examined. Moreover, changes in COP location on the starting block surface have only been reported for two sprinters, and the general shape of changes in COP location for sprinters is still unknown. Elucidating changes in COP on the starting block surface would provide insight into the force production manner of one of the most powerful human movements.

The purpose of this study was to examine the association of block clearance performance with COP location on the starting block surface. Knowledge gained from the examination of the association of the block clearance performance with COP locations would be useful for sprinters and coaches when they try to improve block clearance performance.

MATERIALS AND METHODS

Participants

Twenty one male sprinters (mean ± SD: age, 20.4 ± 1.4 y; stature, 1.73 ± 0.06 m; body mass, 65.7 ± 4.3 kg; personal best 100-m time, 11.24 ± 0.41 s) participated in this study. Before the experiment, all participants were fully informed of the aim, risks of involvement, and experimental conditions of the study, and gave their written consent. This study was approved by the research ethics committee of the institute.

Experiments

After warming up, the participants wearing their own spiked shoes performed two maximal effort 60 m sprints from starting blocks with a rest period of 10 min between the trials. The toes of all the participants did not touch the ground and were located at the front edge of the block surface. Two force platforms (TF-32120, Tec Gihan, Uji, Japan; 1,000 Hz), which can measure forces applied by feet separately during block clearance, were used to measure the ground reaction forces (GRFs). A starting block rail (Super III NF155B, Nishi, Tokyo, Japan), which is permitted for use in official races, was bolted at four locations to the force platform covered by athletic track surface (see Ohshima et al., 2019 for detail). Thus, the block itself could be relocated easily, and in exactly the same ways as it could in a race. Sprint time at the 10-m mark was measured using a photo-cell system (TC Timing System, Brower, Draper, UT, USA), and an electric starting gun connected to an operating computer of force platforms provided the start signal, and initiated the timer and recording of GRF.

Twenty one small retro-reflective markers (11 mm in diameter) were affixed to the surface of each starting block (**Figure 1**). Before the trials, the locations of the markers on the starting block surface, which are necessary for coordinate transformation, were determined using a motion capture system (Raptor-E, Motion Analysis Corporation, Santa Rosa, CA, USA; 100 Hz, 10 cameras) for all combinations of block locations and angles (17 locations and five angles) for each block (see Ohshima et al., 2019 for detail). The affixed markers on the starting block surface were removed after the coordinates were recorded. Through this procedure, COP in any combination of block locations and angles could be calculated. The location and angle of each block for each participant was recorded at the trial. The block location and angle of the two blocks were arranged by each participant for his suitable locations and angles.

Data Processing

Based on the 10 m time, the fastest trial for each participant was adopted for the following data processing. GRF signals were smoothed with a fifth-order spline filter (Woltring, 1986). The cut-off frequency was 50 Hz (Nagahara et al., 2017, 2018a,b). Using a previously validated method (Ohshima et al., 2019), changes in COP location on the block surface during the block clearance for each block was calculated by a simple coordinate transformation using the obtained marker coordinates, GRF

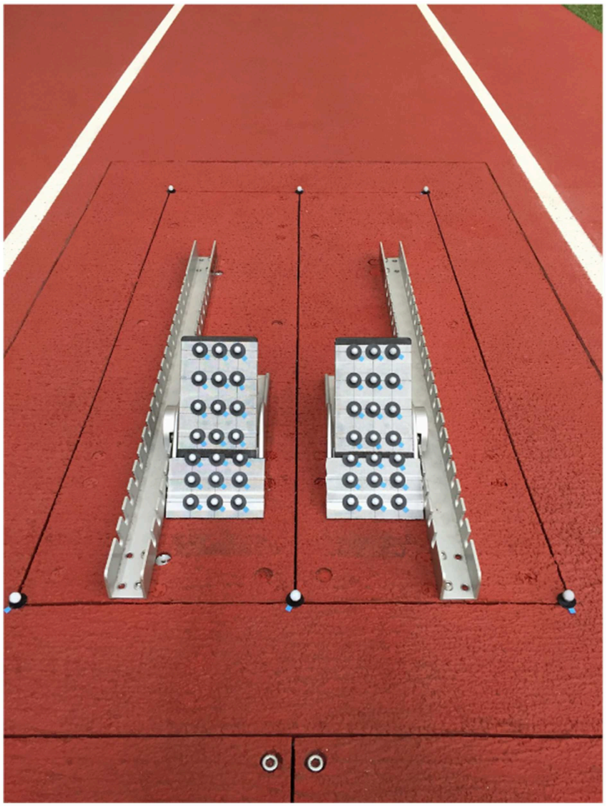

FIGURE 1 | Depiction of the experimental set-up for obtaining coordinates of 21 markers on each of the starting blocks for the COP calculation including the force platforms, starting blocks and rails, and markers on the starting blocks.

signals and moment data around the center of the force platform at the ground level. Briefly, COP values were calculated by separating the starting block surface into six tandem parts, using each of three markers on the block surface for the block coordinate system. In the case of the lower part, the origin of starting block coordinate system was set at the lowest and far-right marker on the block surface in **Figure 1**, while the block coordinate system was made adopting the other two markers which were located at the lowest and far-left and at the second lowest and far-right, respectively, on the starting block. Using a simultaneous equation shown below, COP on the block surface in the global coordinate system was calculated.

$$\left(\begin{bmatrix} \vec{r}_x^{\,OB} \\ \vec{r}_y^{\,OB} \\ \vec{r}_z^{\,OB} \end{bmatrix} + \begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,3} \\ a_{2,1} & a_{2,2} & a_{2,3} \\ a_{3,1} & a_{3,2} & a_{3,3} \end{bmatrix} \cdot \begin{bmatrix} \vec{r}_x^{\,BP} \\ \vec{r}_y^{\,BP} \\ \vec{r}_z^{\,BP} \end{bmatrix}\right) \times \begin{bmatrix} {}^O f_x \\ {}^O f_y \\ {}^O f_z \end{bmatrix} + \begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,3} \\ a_{2,1} & a_{2,2} & a_{2,3} \\ a_{3,1} & a_{3,2} & a_{3,3} \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ {}^B n_z^{couple} \end{bmatrix} = \begin{bmatrix} {}^O n_x^{total} \\ {}^O n_y^{total} \\ {}^O n_z^{total} \end{bmatrix} \quad (1)$$

where $\vec{r}_x^{\,OB}$, $\vec{r}_y^{\,OB}$, and $\vec{r}_z^{\,OB}$ are coordinates of the origin of the starting block coordinate system (B) in the force platform (global) coordinate system (O), in which the origin is set at the center of force platform at ground level; $a_{1,1}$ to $a_{3,3}$ are the components of a coordinate transformation matrix of the starting block coordinate system (B) to the force platform coordinate system (O); $\vec{r}_x^{\,BP}$, $\vec{r}_y^{\,BP}$, and $\vec{r}_z^{\,BP}$ are the coordinates of the COP (P) in the starting block coordinate system (B); ${}^O f_x$, ${}^O f_y$, and ${}^O f_z$ are applied forces onto the ground in the force platform coordinate system (O); ${}^B n_z^{couple}$ is the free moment applied on the x'y' (block surface) plane of the starting block coordinate system (B); and ${}^O n_x^{total}$, ${}^O n_y^{total}$, and ${}^O n_z^{total}$ are applied moments around the origin of the force platform coordinate system (O). In the case where the COP (P) is on the x'y' plane of the starting block coordinate system (B), $\vec{r}_z^{\,BP}$ is equal to zero. When the COP moved below the origin of the used coordinate system, the coordinate system for calculating the COP was changed to the lower one.

The onset of the force production and toe-off for each leg were determined using the first derivative of the GRF applied perpendicularly to the block surface with a threshold of >500 N/s (Brazil et al., 2017). Toe-off was defined when the GRF applied perpendicularly to the block surface next fell below 50 N (Brazil et al., 2017). Horizontal velocity was calculated integrating mass-specific filtered anteroposterior GRF with adjusting the influence of air resistance in accordance with previous studies (Colyer et al., 2018; Nagahara et al., 2019). Horizontal velocity was combined with support duration to provide average horizontal external power (AHEP), which was considered the key performance criterion, in reference to Bezodis et al. (2010). AHEP was divided by body mass.

Statistical Analyses

Descriptive data were presented by means and standard deviations (SDs). The correlation coefficient was calculated to examine relationships between AHEP and COP discrete variables. Statistical parametric mapping (SPM) 1D linear regressions were used to test relationships between AHEP and COP location curves in the anteroposterior and vertical directions (Pataky, 2012). The significance level was set at $p < 0.05$. Threshold values for the interpretation of correlation coefficient as an effect size were 0.1 (small), 0.3 (moderate), 0.5 (large), 0.7 (very large), and 0.9 (extremely large) (Hopkins et al., 2009).

RESULTS

The 10 m time was 2.09 ± 0.07 s. COP locations (the origin is at the middle of two blocks, the front edge of each block and the ground level) and starting block locations (anteroposterior distance between the starting line to the front edge of the block surface), and angles (from ground level) were shown in **Table 1**. For the COP locations on the block surface, mean COP locations in the vertical direction for both legs were positively correlated with AHEP (moderate effect), whereas there were no correlations between the mean COPs in the mediolateral and anteroposterior directions and AHEP (**Table 1** and **Figure 2**). **Figure 3** shows changes in COP locations in the anteroposterior and vertical directions for the front and rear blocks and the results of the SPM analyses. The COP for both legs moved backward and upward (0.042 and 0.042 m for the front block and

TABLE 1 | Mean and SD for AHEP, COP locations and block locations and angles, and relationship of AHEP with other variables.

Variables [units]	Mean ± SD	Correlation coefficient (*P*-value)
AHEP [W/kg]	14.7 ± 1.4	
Front block mediolateral mean COP location [m]	0.098 ± 0.007	0.237 (0.301)
Front block anteroposterior mean COP location [m]	−0.080 ± 0.024	−0.428 (0.052)
Front block vertical mean COP location [m]	0.061 ± 0.022	**0.461 (0.035)**
Rear block mediolateral mean COP location [m]	0.098 ± 0.007	−0.094 (0.686)
Rear block anteroposterior mean COP location [m]	−0.082 ± 0.018	−0.423 (0.055)
Rear block vertical mean COP location [m]	0.064 ± 0.018	**0.499 (0.021)**
Front block location [m]	−0.45 ± 0.05	0.077 (0.739)
Front block angle [°]	48.9 ± 3.8	0.099 (0.669)
Rear block location [m]	−0.69 ± 0.06	−0.144 (0.533)
Rear block angle [°]	53.0 ± 3.5	−0.070 (0.763)

The mediolateral COP values for both sides are shown in positive values.
AHEP, average horizontal external power; COP, center of pressure.
Bold values indicate significant correlations.

0.030 and 0.034 m for the rear block) at first and then forward and downward (0.113 and 0.094 m for the front block and 0.095 and 0.087 m for the rear block) toward the toe-off. The timing of moving COP shifting to forward and downward was earlier in the front block (**Figure 3**). Based on SPM results, AHEP was correlated with front block anteroposterior and vertical COP locations from 12.9 to 20.8% and from 10.4 to 22.2% of the force production phase, respectively, while it was correlated with rear block vertical COP location from 31.9 to 37.4% of the force production phase (**Figure 3**).

DISCUSSION

This study is the first to investigate whether COP locations on the starting block surface are related to sprint start performance. The main findings were that (1) there were positive correlations between the mean vertical COP locations on the starting block surface and AHEP, and (2) the COP locations were correlated with AHEP where the COPs were located at the high and rear on the starting block surface during the force production phase.

The higher mean vertical location of COP on the starting block surface was correlated with greater AHEP for both legs. Moreover, although correlation coefficients between AHEP and the mean anteroposterior location of COP on the starting block surface for both legs came short of the significance level, effect sizes of the corresponding relationships were moderate and were the same as the effect size of the relationships between AHEP and the mean vertical locations of COP on the starting block surface. In contrast, the location and angle of the blocks did not show correlations with AHEP. These results demonstrate that higher and possibly more to the rear COP location on the starting block is advantageous for better sprint start performance regardless of starting block locations and angles. Moreover, COP locations were only correlated with AHEP where the COPs were located at the high and rear on the block surface, indicating that COP location can be a determinant of sprint start performance when it is relatively close to heel, while COP at the initial or terminal location is not decisive for better sprint start performance. Accordingly, COP location on the starting block should be taken into account for achieving better sprint start performance. In order to accomplish the higher and more to the rear COP on the block surface, when COP is located close to heel during the middle phase of the block clearance, suppressing force production at the fore-foot through suppressing ankle plantar flexion during the initial force production duration will possibly be a useful way for sprinters.

The current finding of no correlation between AHEP and block angles are in line with a previous study which revealed no effects of habitual block angle on block power (Schrödter et al., 2016). For the COP locations on the starting block surface, it moved backward and upward at first and then forward and downward toward the toe-off for both legs, and these changes in COP location on the starting block surface are consistent with a previous case report (Ohshima et al., 2019). Moreover, this backward movement of COP on the starting block surface before forward movement is similar to the movement of COP during the vertical jump (Le Pellec and Maton, 2002). Because no study has investigated the relationship of COP location on the starting block surface with the start performance, it is difficult to compare the current results to previous studies.

Higher COP location on the starting block surface will make it possible to shorten the vertical distance between the GRF vector and the whole body center of mass which allows sprinters to efficiently produce the propulsive force, resulting in a better block clearance performance. From the other aspect, higher and more to the rear COP location on the starting block surfaces means that the COP is closer to the ankle joint, indicating that the distance between force application location and the ankle joint center is short. This shorter distance between application location and the ankle joint center allows a sprinter to produce the force on the block with smaller ankle plantar flexion moment, which may possibly enhance the efficiency of force transmission from hip and knee to the ground. The magnitudes of net and propulsive GRFs at the block clearance are decisive for better sprint start performance (Rabita et al., 2015; Bezodis et al., 2019). Moreover, based on the force-time curves, time spans where the correlations were found using SPM analyses are approximately the ranges where the forces rapidly develop. Taken together, the higher and more to the rear COP on the starting block surface, when COP is located close to heel during the middle phase of the block clearance, is likely efficient for producing the large magnitude of force onto the starting block, and this might result in the correlation of AHEP with COP locations.

There are some limitations on the findings of this study. Because a foot location was not recorded in this study, the relationship between foot and COP locations is still unknown. Moreover, relationships of body segment configurations with COP locations and sprint start performance will be an interesting topic of a future study. The participants in this study were only male sprinters and not international level, and thus it is possible

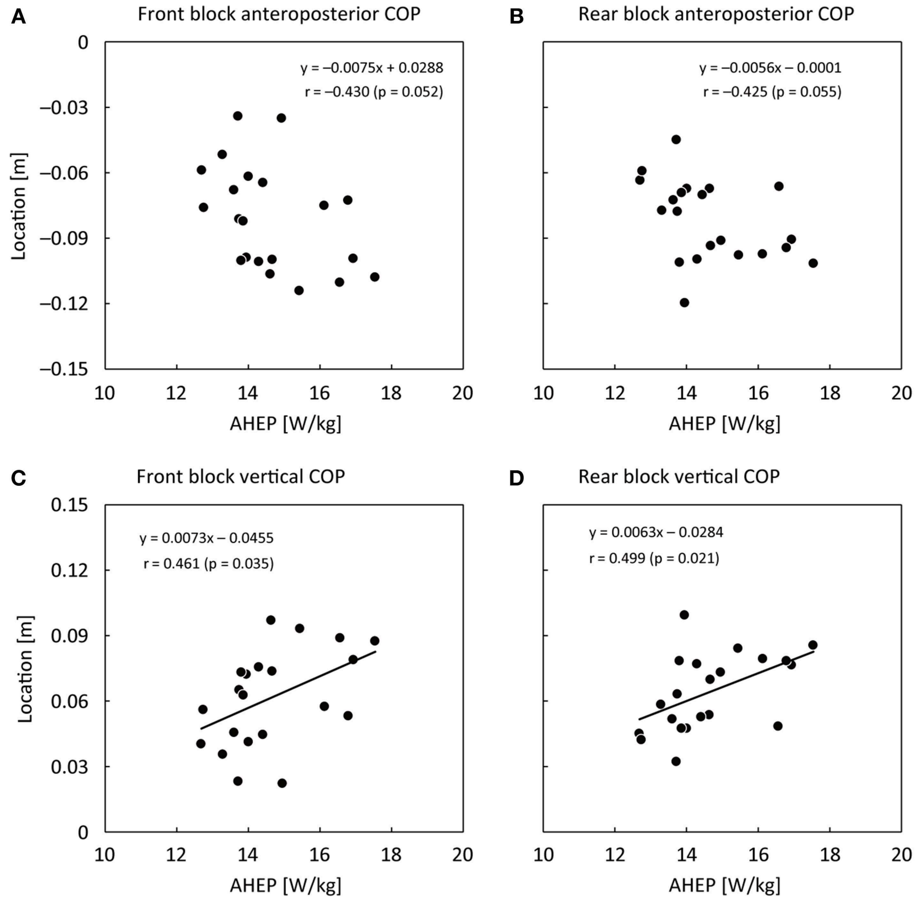

FIGURE 2 | Relationship of AHEP at the start with the front block mean anteroposterior COP location **(A)**, the rear block mean anteroposterior COP location **(B)**, the front block mean vertical COP location **(C)**, and the rear block mean vertical COP location **(D)**.

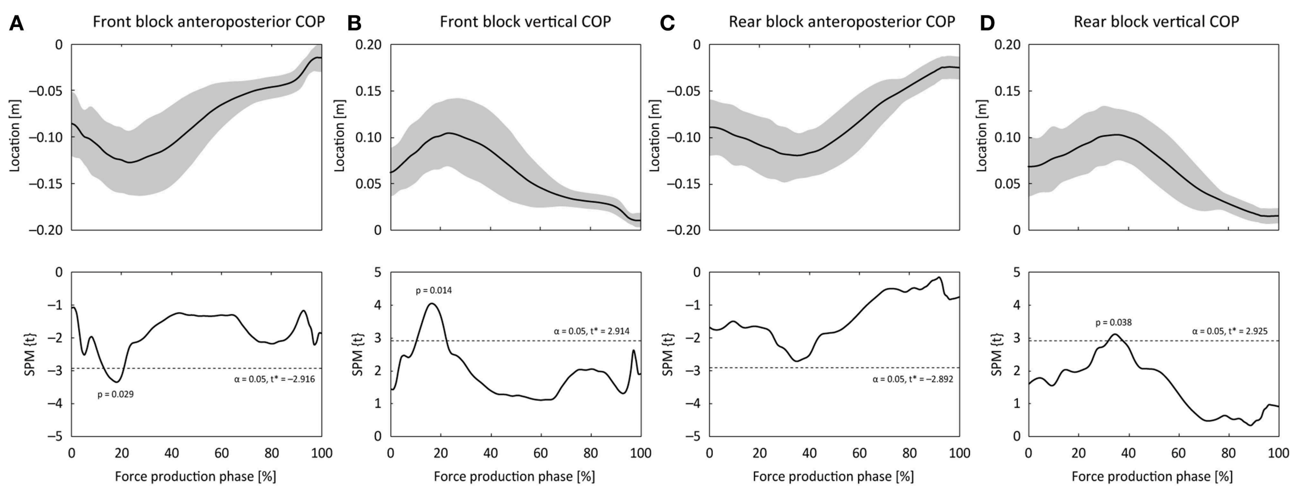

FIGURE 3 | Normalized mean COP curves during the force production phase at the block clearance, and the associated SPM-1D *t*-test results for association of average horizontal external power with each COP location. **(A)** Front block anteroposterior COP, **(B)** Front block vertical COP, **(C)** Rear block anteroposterior COP, **(D)** Rear block vertical COP. The second row of the panels shows SPM-1D linear regression test results. Ranges where the curve being above or below the dotted line indicate statistically significant differences between curves.

that a different conclusion would be derived from hurdlers, female or elite sprinters.

In conclusion, the current results demonstrate that, regardless of the starting block location and angle, better sprint start performance is achieved with a higher and more to the rear COP on the starting block surface when COP is located close to heel during the middle phase of the block clearance. The fact that the COP location is related to sprint start performance will be useful for sprinters and coaches who intend to improve sprint start performance.

DATA AVAILABILITY

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Research ethics committee of the National Institute of Fitness and Sports in Kanoya. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

RN and YO contributed to conceiving, designing, and performing the experiment, to analyzing the data, and to drafting and revising the article. RN performed most of the data analysis and drafting the article.

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Biomechanical Pole Vault Patterns Were Associated With a Higher Proportion of Injuries

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Background: Pole vault is a highly demanding sport where many physical and technical requirements are engaged in performance process. Considering level of energy transferred from athlete's horizontal speed to the pole during pole bending, we can imagine that associated musculoskeletal tensions, in addition to trials accumulation, can increase the risk of (specific) injuries. Given the multiple morphological, physical and technical characteristics of vaulters and ways of pole vaulting, we can hypothesis that some patterns of pole vaults can lead to higher injury risk than others.

Aim: To analyze the potential association between the biomechanical patterns of pole vault and the history of injuries.

Method: We conducted a study over national-level pole vaulters including the prospective collection of pole vault biomechanical data during competition at the national elite indoor championship and youth national indoor championship (U17 and U20), associated with the retrospective collection of their injuries during the 12 preceding months through an online questionnaire.

Results: Among the 88 pole vaulters participating in these championships, 62 (70.5%) accepted to participated in this study, and their pole vault biomechanical and injury data were collected. 77.4% reported having presented at least one injury during the 12 preceding months. One biomechanical parameter related to the take-off phase (lower H2, i.e., height of the grip (superior) hand from the ground when the athlete subsequently took off from the ground) and some biomechanical parameters related to the terminal phase of the run-up phase (higher Spd [i.e., speed between 10 and 5 meters to the box), SL_{adj} (last stride adjustment), SL_{var} (stride length variation), t_c (contact time)] were significantly associated with higher proportions of all injuries.

Conclusion: Biomechanical pole vault patterns during the competition day were associated with a higher proportion of history of all injuries. Although the injury data collection was retrospective leading to recall bias risk, and do not allow determining cause-consequence relationships regarding biomechanical patterns and injury occurrence, this present study is the first to analyze potential association between the biomechanical pole vault patterns and injury occurrence, which is of great help to provide hypotheses/ideas to design future studies and to move forward into prevention measures.

Keywords: sports injury prevention, biomechanics, pole vault, epidemiology, track and field, top-level athletes, injury risk

INTRODUCTION

Pole vault is a highly demanding specialty of Athletics, in the discipline of jumps (https://www.iaaf.org/disciplines), where many physical and technical requirements are engaged in performance process (Zagorac et al., 2008; Cassirame et al., 2017). This large combination of capabilities needed to perform at best includes for instance running speed, strength and agility, as well as important technical skills (Ekevad and Lundberg, 1997; Frère et al., 2010; Linthorne and Weetman, 2012; Schade and Arampatzis, 2012; Cassirame et al., 2017).

Pole vault training consequently includes physical and technical training, and can be processed differently by each coach considering his own approach of the problem and the individual characteristics of pole vaulters (Gross et al., 2019). Specific technical points can be train in isolation. However, pole vault training often includes a high number of vault trials to improve and optimize the integration of the global pole vault skill/pattern by the vaulter. Pole vault trial is generally described by 4 successive phases: (1) run-up, (2) pole planting and take-off, (3) pole bending, and (4) pole straightening and bar clearance (**Figure 1**) (Frère et al., 2010). During those phases, the athlete could benefit from the elastic properties of the vaulting pole to gain in mechanical energy and achieve a high performance (Schade et al., 2004). Considering the level of energy transferred from horizontal speed of vaulter to the pole during pole planting, take-off, and pole bending phases (Ekevad and Lundberg, 1997; Frère et al., 2010; Linthorne and Weetman, 2012; Schade and Arampatzis, 2012), we can imagine that such musculoskeletal tensions/constraints can be associated with an increased risk of (specific) injuries, which increase with the accumulation of trials. In addition, given the multiple possibilities of morphological, physical and technical characteristics of the vaulters, and thus, the multiple ways to perform the pole vault, we can hypothesis that some patterns of pole vaults lead to higher injury risk than others.

The pole vault practice indeed bears the risk of injuries (Rebella et al., 2008; Rebella, 2015). An injury rate of 26.4 injuries per 100 athletes per season (95% confidence intervals, 18.6–36.4) and 7.1 injuries per 1,000 athletic-exposures (95% confidence intervals, 5.0–9.8) has been reported in 140 high school pole vaulters aged 16.1 ± 1.2 years (Rebella et al., 2008). In 135 collegiate pole vaulters aged 20.6 ± 1.4 years, Rebella (2015) reported a quite similar injury incidence of 7.9 injuries per 1,000 athlete-exposures, with 15% of injuries leading to season-ending, although the majority of injuries lead to an average time-loss of 9 days (Rebella, 2015). But it is important to note that catastrophic injuries have also been described (Boden et al., 2001, 2012). In other epidemiological studies on injuries in athletics, pole vaulters were included in the groups of jumpers making impossible the distinction of the specific injury risk and characteristics of pole vaulters (Watson and Dimartino, 1987; D'Souza, 1994; Bennell and Crossley, 1996; Edouard et al., 2011, 2015a,b; Jacobsson et al., 2012, 2013).

Although few data are available on pole vaulters' injuries (Rebella et al., 2008; Rebella, 2015), making the need of further studies, the prevention of injuries in pole vaulters seems to be an important challenge for athletes and all stakeholders around them, both in a sports performance and health protection strategies. Better understanding the injury mechanisms and risk factors represents a relevant research direction to move forward into prevention (van Mechelen et al., 1992; Bahr and Krosshaug, 2005). Focusing on injury mechanisms, Rebella (2015) reported that the technique play an important role in the occurrence of injuries: vaulting mechanisms accounted for 67.1% of all injuries, with 32.8% occurring during the plant/take-off phase. Almost all back injuries and majority of shoulder and hamstring injuries occurred during the plant/take-off. These results support that better understanding the biomechanics of pole vault is of interest in this injury prevention perspective.

To date, no study investigated the association between the occurrence of injuries related to pole vault practice and the athletes' characteristics and technical way to vault. Literature (Angulo-Kinzler et al., 1994; Schade et al., 2004) and our own observations during last 10 years of athlete's follow-up highlighted large variabilities in inter-individual characteristics and pole vault mechanical parameters (take-off speed, grip height, pole stiffness, stride regulation, take-off position, …). Given the relationships between pole vault biomechanics and injury mechanisms (Rebella, 2015), it seems of interest to determine whether some pole vault technical and performance determinants would be associated to injuries. In this context, the aim of the present study was to analyze the potential association between the biomechanical patterns of pole vault and the history of injuries. We hypothesized that pole planting and

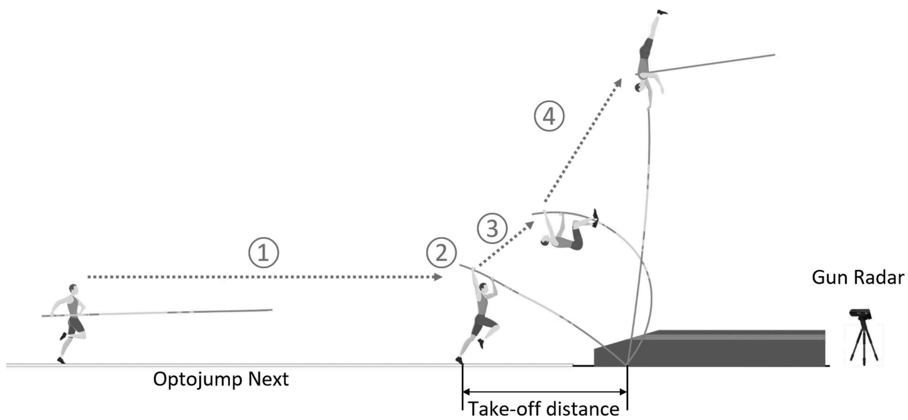

FIGURE 1 | Description of the pole vault trial by the 4 successive phases: (1) run-up, (2) pole planting and take-off, (3) pole bending, and (4) pole straightening and bar clearance (Frère et al., 2010), and of the experimental setup of pole vault biomechanical measurements.

take-off phase parameters can be associated with risk of injuries considering impact and force applied in this moment to initiate energy conversion.

METHODS

Study Design and Procedure

We conducted a study over national-level pole vaulters including the prospective collection of pole vault biomechanical data during a competition in the context of the national Elite indoor championship and youth national indoor championship (U17 and U20) and the retrospective collection of injuries during the 12 preceding months through an online questionnaire. Those data were collected as part of national Elite follow-up programme from French Athletics Federation (https://www.athle.fr). The study protocol was reviewed and approved by the Saint-Etienne University Hospital Ethics Committee (Institutional Review Board: IORG0007394; IRBN322016/CHUSTE).

Population

We proposed to all pole vaulters participating at national Elite indoor championship and youth national indoor championship (U17 and U20) to be volunteer for this study. Pole vaulters were included if they were registered with the French Athletics Federation, had no contra-indication for athletics participation, were able to participate at the pole vault competition, were able to read and reply to survey in French sent by internet, and accepted to participate at the study.

The day of the competition, athletes (and their parents when minors) were informed about the study aim and procedure, and gave their consent to participate and their data being used for research.

Injury Data Collection

At the time of the competition the included pole vaulters were asked to complete an online survey about number of year of pole vault practice, mean number of hours of athletics training per week, if they had an injury history during the last 12 months, and if they have currently a pain or discomfort during pole vault. For the purpose of the study injury was defined as: "Any pain, discomfort, or lesion of the musculoskeletal system (e.g., bones, muscles, tendons, ligaments...), which occurred during sports practice (i.e., training or competition), regardless of the consequences on sport and medical attention, occurring in the last 12 months." If athletes replied yes, they were asked to detail for each injury the injury location (e.g., hamstring, ankle…).

Pole Vault Biomechanical Data Acquisition

Pole vault biomechanical data were collected, in the context of a national level competition, during run-up until take-off with the similar set-up than during previous studies (Cassirame et al., 2018). Twenty meters of optoelectronic system (Optojump Next Microgate, Bolzano, Italy) was installed on the official lane to measure run-up kinematics. Due to the landing mat, optoelectronic system could not be installed until the planting box and was installed up until 2.00 or 2.20 m before the box (**Figure 1**). This material permits measurement of contact time on the floor (t_c), aerial time (t_a), stride rate (SR), and stride length (SL). SL asymmetry (SL_{asy}) was calculated as the absolute difference of distance covered on three left-foot strides minus the distance covered on three right-foot strides. SL variability (SL_{var}) was calculated as the mean of the differences between stride length over successive steps. SR, SL, SL_{asy}, SL_{var}, t_a, and t_c were measured and averaged from the 3rd up to 8th last stride of the approach. Last two strides of the run-up were not take into account because they are commonly used to adjust take-off distance and are not representative of the running kinematic (Makaruk et al., 2016). Finally, last stride adjustment (SL_{adj}) was calculated as the final SL minus the penultimate SL. Negative SL_{adj} indicated a reduction in the last SL, and a positive value indicated a longer final stride (Cassirame et al., 2018). Position of the foot at take-off (PoTk) was calculated using position data output from the optoelectronic system and the distance from the planting box (**Figure 1**).

Horizontal running velocity was measured using Radar gun (Stalker Pro II, Stalker ltd, Plano, TX) positioned behind the landing mat at 1.4 meter height offering no angle deviation with athletes trajectory (**Figure 1**). Data output from radar were collected at 46.9 Hz by MookyStalker software (Matsport, Saint-Ismier, France) and synchronized with the Optojump Next system to calculate approach speed between 10 and 5 meters to the box (Spd) and speed increase in last 5 m of the run-up (ΔSpd).

During the take-off phase, a video analysis was performed with a Gopro Hero 5 camera (San Mateo, California, United-States) using a sampling rate of 240 frames per seconds and a resolution of 1280 × 720 pixels. The camera was positioned at a distance of 4 m perpendicular to the lane at a 3.5 m distance from the box to avoid parallax error. Before each competition, calibration videos were collected using a calibration stick of known length (2.40 m) in the plane of measurement. Video analyzes were manually performed with Kinovea software 08.15 (Joan Charmant & Contributors, Bordeaux, France) to output several length measurements in two different positions. The Position 1 occurred when the athlete was in contact with the ground at the instant of pole plant in the box, and the Position 2 occurred when the athlete subsequently took off from the ground (**Figure 2**). At both positions, the height of the grip (superior) hand from the ground was measured and noted as H1 and H2 for Positions 1 and 2, respectively. In addition, the anteroposterior distance between the grip hand and the take-off foot's toes was calculated at the two positions and noted as U1 and U2 (**Figure 2**). If the grip hand was posterior to the toes, this value was negative. From these four measurements, ΔH and ΔU were calculated in order to obtain vertical and horizontal displacements of the grip hand between the two positions. ΔH and ΔU were calculated as follows: ΔH = H2–H1 and ΔU = U2–U1. To complete this analysis, the distance between hands (HD) and the distance between the grip hand and pole extremity was also measured. This last measurement permits to calculate the grip height (Grip) used by athlete during trials.

Finally, data related to the poles used during the competition were collected from coach and/or athlete interview. For each trial, pole length and stiffness index (P_{Stiff}) were collected. Pole length information was use to deduct grip (Grip) used by athlete use measurement processed by video analysis (Distance upper hand to extremity of the pole in the box).

Data Analyzes

Descriptive analyzes were performed with the total population, and separated into female and male pole vaulters, and then divided according to age categories (youth, junior and adult), using frequency with percentages [and 95% Confidence Intervals (95%CI)] for categorical data, and mean and standard deviations (± SD) for continuous variables. Normal distribution of the data was checked by the Shapiro-Wilk normality test. A two-way (sex × age category) ANOVA was performed to analyze the potential differences in pole vault biomechanical parameters according to these factors. A Chi^2 test was used to compare injured pole vaulters' proportions according to sex and age category.

In order to analyze the association between pole vault biomechanics and history of injuries (outcomes were: all injuries, and the main reported injury location: hamstring injuries, quadriceps injuries, ankle injuries, upper extremity injuries, and pain when practicing pole vault), we used a logistic stepwise regression model including several explanatory variables selected after collinearity analysis (Spd, ΔSpd, SL, SR, t_a, t_c, SL_{adj}, SL_{asy}, SL_{var}, P_{Stiff}, Grip, PoTk, HD, H1, U1, H2, U2, ΔH, ΔU) and adjusted for sex and age category. The significance level was set at $P < 0.05$. Analyzes were performed using Excel (Office, Microsoft®, 2017) and JASP (JASP Team software, Version 0.8.5.1, University of Amsterdam, Netherlands).

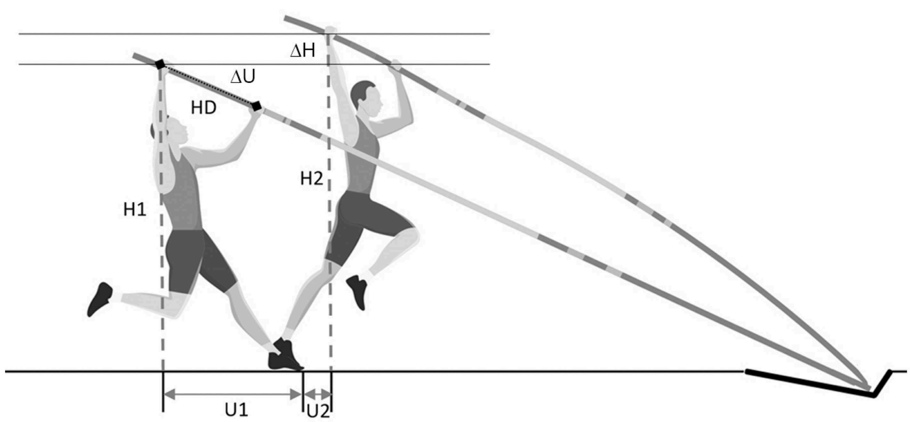

FIGURE 2 | Description of the analysis of the take-off position: Position 1 occurred when the athlete was in contact with the ground at the instant of pole plant in the box. Position 2 occurred at the instance that the athlete subsequently took off from the ground. At both positions, the height of the grip (superior) hand from the ground was measured and noted as H1 and H2 for Positions 1 and 2, respectively. In addition, anteroposterior distance between the grip hand and the take-off foot's toes was calculated at the two positions and noted as U1 and U2. From these four measurements, ΔH and ΔU were calculated in order to obtain vertical and horizontal displacements of the grip hand between the two positions. ΔH and ΔU were calculated as follows: ΔH = H2–H1 and ΔU = U2–U1. The distance between hands (HD) and the distance between the grip hand and pole extremity was also measured.

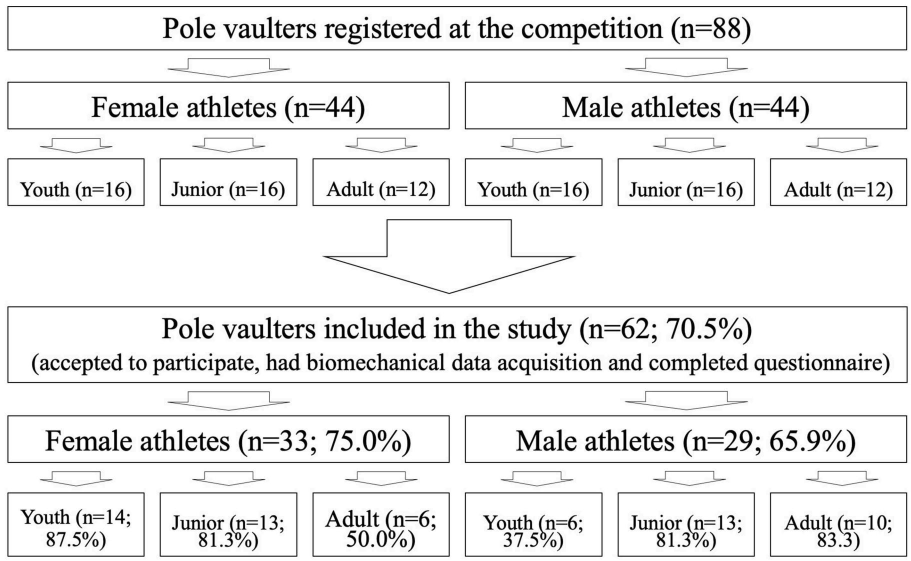

FIGURE 3 | Flow chart of the population inclusion.

RESULTS

Population

Among the 88 pole vaulters registered at the competition, 62 (70.5%) accepted to participate in the present study, had pole vault biomechanical data acquisition, completed the online questionnaire, and were thus included in the present study. The flow chart of the included population is presented in **Figure 3**, and the characteristics of the population in **Table 1**.

History of Injuries

On the 62 pole vaulters, 48 (77.4%) reported having presented at least one injury during the 12 preceding months. Within these 48 athletes, 29 (60.4%) presented with one injury, 14 (29.2%) presented with two, 2 (4.2%) with three, 2 (4.2%) with four, and one (2.1%) with five injuries. Proportions of injured pole vaulters according to injury location are reported in **Table 1**. 4.8% reported having pain during pole vault practice, they are all male adult athletes (**Table 1**).

Pole Vault Biomechanical Parameters

Pole vault biomechanics differed between sex for many parameters: Spd, ΔSpd, SL, SR, t_c, P_{Stiff}, Grip, PoTk, H1, H2, U2; as well as between age category: Spd, ΔSpd, SL, t_c, SL_{adj}, Grip, PoTk, HD, H1, H2, ΔH; with sex × age interaction for P_{Stiff} and Grip (**Table 1**).

Pole Vault Biomechanical Parameters and History of Injuries

Results of the logistic regressions are presented in **Table 2**. H2, training time per week, SL_{adj}, Spd, t_c, and SL_{var} were significantly associated with history of all injuries [although the model was not significant ($p = 0.067$)]. Duration of training per week and ΔSpd were significantly associated with history of ankle injuries [although the model was not significant ($p = 0.141$)]. Logistic regressions were not significant for history of hamstring injuries, and have been not performed for quadriceps injuries, upper extremity injuries and pain when practicing pole vault, due to the small number of injuries in these respective categories.

DISCUSSION

The main findings of the present study were that some biomechanical pole vault parameters were associated with a higher proportion of history of all injuries. Parameters related to the take-off phase (lower H2) and to the terminal phase of the run-up phase (higher Spd, SL_{adj}, SL_{var}, t_c), as well as higher volume of training per week, were associated with a higher proportion of history of all injuries. These findings partially confirm our hypothesis. We hypothesized that pole planting and take-off phase parameters can be associated with risk of injuries considering impact and force applied in this moment to initiate energy conversion. Our results reported that one biomechanical parameter related to the take-off phase and some biomechanical parameters related to the terminal phase of the run-up phase (and preparation of the planting/take-off phase) were significantly associated with a higher proportion of history of all injuries. However, given the retrospective design of the injury data collection, it is not possible to conclude about the cause or consequence of the present biomechanical parameters with regards to their role in the injury occurrence.

Horizontally-Based Vaulting Techniques Associated With Injuries

Our present results reported that a lower H2 [i.e., height of the grip (superior) hand from the ground when the athlete took off from the ground], a higher stride length adjustment (i.e., a

TABLE 1 | Characteristics of the included pole vaulters with regards to pole vault practice and biomechanics and history of injuries.

	Total	Female athletes			Male athletes			Sex	Age category	Sex x age category
		Youth	Junior	Adult	Youth	Junior	Adult			
	***n* = 62**	***n* = 14**	***n* = 13**	***n* = 6**	***n* = 6**	***n* = 13**	***n* = 10**			
History of pole vault practic										
Number of years of practice (years)	6.69 ± 4.47	3.9 ± 1.8	4.4 ± 1.2	10.8 ± 4.2	4.8 ± 1.3	6.2 ± 1.7	12.9 ± 6.1	$F_{(1, 56)} = 3.435$; $p = 0.069$	**$F_{(2, 56)} = 28.855$; $p < 0.001$**	$F_{(2, 56)} = 0.182$; $p = 0.834$
Training per week (hours)	9.53 ± 4.73	7.6 ± 3.2	8.0 ± 2.9	13.0 ± 1.8	6.1 ± 2.5	9.8 ± 4.4	13.9 ± 7.0	$F_{(1, 56)} = 0.117$; $p = 0.734$	**$F_{(2, 56)} = 10.723$; $p < 0.001$**	$F_{(2, 56)} = 0.796$; $p = 0.456$
Pole vault biomechanics										
Run-up phase										
Spd (m/s)	7.81 ± 0.86	6.8 ± 0.5	7.3 ± 0.3	7.7 ± 0.1	8.2 ± 0.1	8.5 ± 0.3	9.0 ± 0.2	**$F_{(1, 56)} = 239.019$; $p < 0.001$**	**$F_{(2, 56)} = 25.743$; $p < 0.001$**	$F_{(2, 56)} = 0.596$; $p = 0.555$
ΔSpd (m/s)	0.13 ± 0.14	0.10 ± 0.11	0.11 ± 0.10	–0.6 ± 0.04	0.21 ± 0.14	0.28 ± 0.11	0.11 ± 0.10	**$F_{(1, 56)} = 29.401$; $p < 0.001$**	**$F_{(2, 56)} = 12.904$; $p < 0.001$**	$F_{(2, 56)} = 0.571$; $p = 0.568$
SL (cm)	192.95 ± 16.62	176.5 ± 12.2	182.5 ± 9.9	197.5 ± 12.2	190.2 ± 8.6	203.2 ± 7.7	215.2 ± 7.0	**$F_{(1, 56)} = 44.985$; $p < 0.001$**	**$F_{(2, 56)} = 23.168$; $p < 0.001$**	$F_{(2, 56)} = 0.673$; $p = 0.514$
SR (stride/s)	3.94 ± 0.22	3.8 ± 0.1	3.8 ± 0.2	3.8 ± 0.2	4.1 ± 0.1	4.1 ± 0.2	4.2 ± 0.2	**$F_{(1, 56)} = 59.615$; $p < 0.001$**	$F_{(2, 56)} = 1.967$; $p = 0.149$	$F_{(2, 56)} = 0.020$; $p = 0.980$
t_a (s)	0.12 ± 0.01	0.12 ± 0.01	0.12 ± 0.01	0.13 ± 0.01	0.12 ± 0.01	0.12 ± 0.01	0.12 ± 0.01	$F_{(1, 56)} = 1.601$; $p = 0.211$	$F_{(2, 56)} = 2.146$; $p = 0.126$	$F_{(2, 56)} = 1.319$; $p = 0.276$
t_c (s)	0.13 ± 0.01	0.14 ± 0.01	0.14 ± 0.01	0.13 ± 0.00	0.12 ± 0.1	0.12 ± 0.1	0.12 ± 0.1	**$F_{(1, 56)} = 22.878$; $p < 0.001$**	**$F_{(2, 56)} = 4.145$; $p = 0.021$**	$F_{(2, 56)} = 1.284$; $p = 0.285$
SL_{adj} (cm)	–13.87 ± 13.10	–16.9 ± 12.6	–6.3 ± 14.0	–17.8 ± 11.5	–14.6 ± 7.3	–11.1 ± 12.4	–20.3 ± 14.1	$F_{(1, 56)} = 0.229$; $p = 0.634$	**$F_{(2, 56)} = 3.587$; $p = 0.034$**	$F_{(2, 56)} = 0.401$; $p = 0.671$
SL_{asy} (cm)	–0.41 ± 8.58	–2.2 ± 10.1	0.8 ± 8.6	2.6 ± 8.6	1.2 ± 12.2	–0.4 ± 5.6	–2.2 ± 8.3	$F_{(1, 56)} = 0.122$; $p = 0.728$	$F_{(2, 56)} = 0.039$; $p = 0.962$	$F_{(2, 56)} = 0.888$; $p = 0.417$
SL_{var} (cm)	8.33 ± 4.51	9.8 ± 5.2	7.4 ± 4.4	9.4 ± 6.2	9.3 ± 4.4	6.9 ± 3.7	8.1 ± 3.8	$F_{(1, 56)} = 0.410$; $p = 0.525$	$F_{(2, 56)} = 1.545$; $p = 0.222$	$F_{(2, 56)} = 0.031$; $p = 0.969$
Pole planting and take-off phase										
P_{Stiff} (cm/50 lb)	21.10 ± 3.71	22.9 ± 2.1	23.3 ± 3.6	24.8 ± 1.7	21.2 ± 3.4	18.8 ± 2.1	16.4 ± 1.4	**$F_{(1, 56)} = 51.947$; $p < 0.001$**	$F_{(2, 56)} = 1.370$; $p = 0.262$	**$F_{(2, 56)} = 6.994$; $p = 0.002$**
Grip (m)	4.24 ± 0.38	3.8 ± 0.2	4.0 ± 0.2	4.1 ± 0.1	4.4 ± 0.3	4.6 ± 0.1	4.8 ± 0.1	**$F_{(1, 56)} = 216.716$; $p < 0.001$**	**$F_{(2, 56)} = 16.142$; $p < 0.001$**	**$F_{(2, 56)} = 0.744$; $p = 0.048$**
PoTk (m)	3.26 ± 0.46	2.8 ± 0.3	2.9 ± 0.2	3.1 ± 0.2	3.5 ± 0.2	3.7 ± 0.2	3.8 ± 0.2	**$F_{(1, 56)} = 142.881$; $p < 0.001$**	**$F_{(2, 56)} = 6.210$; $p = 0.004$**	$F_{(2, 56)} = 0.511$; $p = 0.603$
HD (cm)	60.95 ± 9.51	61.1 ± 8.3	55.2 ± 7.7	64.3 ± 5.1	59.7 5.6	58.4 ± 12.8	70.3 ± 4.7	$F_{(1, 56)} = 1.300$; $p = 0.259$	**$F_{(2, 56)} = 7.180$; $p = 0.002$**	$F_{(2, 56)} = 0.766$; $p = 0.470$
H1 (cm)	187.98 ± 22.03	183.9 ± 8.0	172.4 ± 23.4	187.7 ± 8.6	201.7 1.8	183.8 ± 29.8	211.3 ± 10.5	**$F_{(1, 56)} = 12.149$; $p < 0.001$**	**$F_{(2, 56)} = 7.097$; $p = 0.002$**	$F_{(2, 56)} = 0.525$; $p = 0.595$

(Continued)

TABLE 1 | Continued

	Total	Female athletes			Male athletes			Sex	Age category	Sex x age category
		Youth	Junior	Adult	Youth	Junior	Adult			
	$n = 62$	$n = 14$	$n = 13$	$n = 6$	$n = 6$	$n = 13$	$n = 10$			
U1 (cm)	−39.68 ± 18.01	−42.6 ± 17.0	−40.9 ± 11.5	−46.1 ± 16.6	−44.7 ± 26.4	−26.5 ± 15.2	−44.3 ± 20.5	$F_{(1, 56)} = 1.004$; $p = 0.321$	$F_{(2, 56)} = 2.763$; $p = 0.072$	$F_{(2, 56)} = 1.342$; $p = 0.270$
H2 (cm)	196.34 ± 21.17	193.0 ± 7.1	184.8 ± 20.8	194.9 ± 12.3	209.5 ± 6.0	190.0 ± 31.3	217.1 ± 10.6	$\mathbf{F_{(1, 56)} = 8.351}$; $\mathbf{p = 0.005}$	$\mathbf{F_{(2, 56)} = 5.548}$; $\mathbf{p = 0.006}$	$F_{(2, 56)} = 1.096$; $p = 0.341$
U2 (cm)	−22.79 ± 12.88	−25.5 ± 10.4	−29.5 ± 13.4	−24.1 ± 9.7	−21.1 ± 20.4	−13.5 ± 11.0	−22.7 ± 9.0	$\mathbf{F_{(1, 56)} = 4.848}$; $\mathbf{p = 0.032}$	$F_{(2, 56)} = 0.165$; $p = 0.848$	$F_{(2, 56)} = 2.100$; $p = 0.132$
ΔH (cm)	16.89 ± 10.86	17.1 ± 10.6	11.4 ± 7.5	22.0 ± 8.2	23.6 ± 11.8	13.0 ± 9.9	21.7 ± 13.3	$F_{(1, 56)} = 0.841$; $p = 0.363$	$\mathbf{F_{(2, 56)} = 5.339}$; $\mathbf{p = 0.008}$	$F_{(2, 56)} = 0.484$; $p = 0.619$
ΔU (cm)	8.36 ± 7.95	9.1 ± 4.1	12.4 ± 15.3	7.2 ± 4.6	7.8 ± 5.6	6.2 ± 2.7	5.9 ± 3.4	$F_{(1, 56)} = 1.902$; $p = 0.173$	$F_{(2, 56)} = 0.606$; $p = 0.549$	$F_{(2, 56)} = 0.673$; $p = 0.514$
History of injuries										
Proportion of injured pole vaulters during the 12 preceding months (95%CI)										
All injuries	77.4 (±10.4)	64.3 (±25.1)	84.6 (±19.6)	100.0 (±0.0)	66.7 (±37.7)	84.6 (±19.6)	70.0 (±28.4)	$Chi^2 = 0.076$; $p = 0.783$	$Chi^2 = 2.269$; $p = 0.263$	
Hamstring	22.6 (±10.4)	14.3 (±18.3)	23.1 (±22.9)	66.7 (±37.7)	30.8 (±25.1)	10.0 (±18.6)	17.2 (±13.7)	$Chi^2 = 0.888$; $p = 0.346$	$Chi^2 = 2.779$; $p = 0.249$	
Quadriceps	9.7 (±7.4)	21.4 (±21.5)	7.7 (±14.5)	16.7 (±29.8)	0.0 (±0.0)	7.7 (±14.5)	3.4 (± 6.6)	$Chi^2 = 2.419$; $p = 0.120$	$Chi^2 = 0.980$; $p = 0.612$	
Ankle	17.7 (±9.5)	14.3 (±18.3)	23.1 (±22.9)	0.0 (±0.0)	16.7 (±29.8)	7.7 (±14.5)	40.0 (±30.4)	$Chi^2 = 0.324$; $p = 0.569$	$Chi^2 = 0.780$; $p = 0.677$	
Upper extremity	6.5 (±6.1)	7.1 (±13.5)	0.0 (±0.0)	0.0 (±0.0)	16.7 (±29.8)	7.7 (±14.5)	10.0 (±11.1)	$Chi^2 = 1.368$; $p = 0.242$	$Chi^2 = 0.711$; $p = 0.701$	
Proportion of pole vaulters with pain during practice (%)	4.8 (±5.3)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	30.0 (±28.4)	$Chi^2 = 3.587$; $p = 0.058$	$\mathbf{Chi^2 = 9.064}$; $\mathbf{p = 0.011}$	

Spd, speed between 10 and 5 meters to the box; ΔSpd, speed increase in last 5 meter of the run-up; SL, stride length; SR, stride rate; t_a, aerial time; t_c, contact time; SL_{adj}, last stride adjustment; SL_{asy}, stride length asymmetry; SL_{var}, stride length variation; P_{Stiff}, pole length and stiffness; Grip, distance upper hand to extremity of the pole in the box; PoTk, position of the foot at take-off; HD, distance between hands; H1, height of the superior hand from the ground at Position 1; U1, antero-posterior displacement of the superior hand from the take-off foot's toes at Position 1; H2, height of the grip (superior) hand from the ground at Position 2; U2, antero-posterior displacement of the superior hand from the take-off foot's toes at Position 2; ΔH, vertical distance traveled by the superior hand between the two positions; ΔU, horizontal distance traveled by the superior hand between the two positions; 95%CI, 95% confidence intervals. Significant differences are highlighted in bold.

TABLE 2 | Results of the logistic regressions (stepwise multiple regression model) analyzing the association between pole vault biomechanics and history of injuries (outcomes were: all injuries, hamstring injuries, ankle injuries).

Models Summaries Model	Number of the model in the stepwise regression	Deviance	AIC	BIC	*p*	Nagelkerke R^2	AUC	Sensitivity	Specificity
History of all injuries	9	35.98	53.978	73.123	0.067	0.588	0.926	0.938	0.643
History of hamstring injuries	3	60.65	66.653	73.034	0.143	0.131	0.693	0.071	0.979
History of ankle injuries	5	43.38	53.379	64.014	0.141	0.345	0.854	0.273	0.941

Coefficients

Model	Number of the model in the stepwise regression	Parameter	Estimate	Standard Error	Odds Ratio	*z*	*p*	95% CI lower bound	95% CI upper bound
History of all injuries	9	(Intercept)	−30.636	17.798	4.955e−14	−1.721	0.085	−65.519	4.248
		H2	**−0.202**	**0.069**	**0.817**	**−2.931**	**0.003**	**−0.338**	**−0.067**
		Training per week	**0.397**	**0.156**	**1.488**	**2.540**	**0.011**	**0.091**	**0.704**
		SL_{adj}	**0.158**	**0.067**	**1.172**	**2.349**	**0.019**	**0.026**	**0.290**
		ΔSpd	**4.278**	**1.550**	**72.110**	**2.759**	**0.006**	**1.239**	**7.317**
		t_C	**276.336**	**114.909**	**1.026e+120**	**2.405**	**0.016**	**51.119**	**501.553**
		SL_{var}	**0.321**	**0.139**	**1.378**	**2.304**	**0.021**	**0.048**	**0.594**
		ΔH	0.104	0.053	1.110	1.953	0.051	−0.000	0.208
		Acc	−7.977	4.748	3.432e−4	−1.680	0.093	−17.284	1.329
History of hamstring injuries	3	**(Intercept)**	**−9.475**	**4.720**	**7.677e−5**	**−2.007**	**0.045**	**−18.726**	**−0.223**
		t_a	61.247	37.447	3.975e +26	1.636	0.102	−12.147	134.641
		Number of years of practice	0.094	0.063	1.099	1.491	0.136	−0.030	0.218
History of ankle injuries	5	**(Intercept)**	**−9.473**	**2.667**	**7.687e −5**	**−3.552**	**<.001**	**−14.700**	**−4.247**
		Training per week	**0.228**	**0.091**	**1.255**	**2.500**	**0.012**	**0.049**	**0.406**
		ΔSpd	**8.709**	**3.657**	**6058.275**	**2.381**	**0.017**	**1.541**	**15.877**
		U2	−0.063	0.032	0.939	−1.954	0.051	−0.126	0.000
		ΔH	0.066	0.043	1.068	1.550	0.121	−0.017	0.150

Presence of the injury problem coded as class 1. Spd, speed between 10 and 5 meters to the box; ΔSpd, speed increase in last 5 meter of the run-up; SL, stride length; SR, stride rate; t_a, aerial time; t_c, contact time; SL_{adj}, last stride adjustment; SL_{asy}, stride length asymmetry; SL_{var}, stride length variation; P_{Stiff}, pole length and stiffness; Grip, distance upper hand to extremity of the pole in the box; PoTk, position of the foot at take-off; HD, distance between hands; H1, height of the superior hand from the ground at Position 1; U1, antero-posterior displacement of the superior hand from the take-off foot's toes at Position 1; H2, height of the superior hand from the ground at Position 2; U2, antero-posterior displacement of the superior hand from the take-off foot's toes at Position 2; ΔH, vertical distance traveled by the superior hand between the two positions; ΔU, horizontal distance traveled by the superior hand between the two positions; 95% CI, 95% confidence intervals; AIC, Aikaike criterion; BIC, Bayes criterion; AUC, Area Under the Curve. Significant differences are highlighted in bold.

less shorter last stride relative to the penultimate one), and a higher horizontal speed (between 10 and 5 m from the planting box), were significantly associated with a higher proportion of history of all injuries. All together, these three predictors reflect a horizontally-based vaulting technique. Indeed, the lesser adjustment in stride length among the two last strides tends to reduce the possibility of reorienting the athlete's velocity toward a higher vertical component. This might lower the value of H2, and cumulated with a high horizontal velocity, generate a highly horizontally and forward oriented take-off. Such a take-off pattern might lower the pole-ground and take-off angle, which likely increase the injury risk (or this could also be the consequence of previous injuries). Indeed, a more horizontal pole reaction force opposed to the athlete may increase the energy dissipated (as heat) within the hyperextended vaulter's body (Linthorne, 2000), and may elongate tissue above their own elastic capabilities. Gainor et al. (1983) found that such mechanisms could be related to back injuries. Back injuries were not one of the main reported injuries in our present studies (only 4 athletes reported having had back injuries during the 12 preceding months, therefore this injury had not been reported as an outcome). But, our results also suggest that such mechanisms would be related with higher proportions of injuries (either a cause or a consequence). Consequently, we can suggest that producing a higher pole-ground and take-off angle could help to decrease this jerk from the pole, and could be a way to prevent/limit the injury risk (or their secondary compensation). In addition, this suggested strategy to reduce injury risk might not be detrimental for the performance, as Arampatzis et al. (1999) found that the best world-class pole vaulters where those who had the highest values of H2. Although, this has not been proven in our present study. Based on these arguments, we can suggest this action as a win-win performance-prevention strategy. In addition, this reinforce the importance of this transitional phase between running and vaulting, and the importance of a very good mastering of the pole vault technique in order to benefit of the energy from run-up phase, and not to undergo this energy with could be a way to incur injury. Nevertheless, given the retrospective nature of the injury data collection, it is not possible to conclude whether this parameter is a cause or a consequence of the injury. Our discussion is thus only an assumption which should be confirmed in future studies.

Training Exposure Should Be at the Center of Attention

Higher number of hours per week spent at training was also associated with a higher proportion of history of all injuries. Training volume per week is also related to the level of practice, and a sign of engagement in the pole vault discipline. Pole vaulting practice and training associated induce many mechanical traumatisms by vault itself, but also by typical exercises used to developed athletes' capabilities. Increased volume of training can also improve numbers of traumatisms and stress on the body during those work phases and generated injuries as already reported in other sports (Damsted et al., 2018; Sugimoto et al., 2019). This result seems quite obvious as a higher exposition to the risk logically can lead to higher rate of the problem. This reinforces the need of using values of injuries reported to the exposure (e.g., number of injuries per 1,000 h of practice) (Nielsen et al., 2019). For practical implication, pole vaulters with high training volume should be at the center of attention in order to limit the occurrence of injuries. Since training is fundamental to improve performance, we do not (never) say that it is needed to limit training to prevent injuries. We think that it is needed to find an optimal balance in training volume and intensity (training load), for instance paying attention to pain and/or fatigue, allowing recovery, in order to promote performance (Soligard et al., 2016).

Perturbation of Running Patterns as a Consequence of Previous Injuries

As previously discussed, future studies should confirm the latter assumptions, since injuries were retrospectively collected and it is not possible to conclude whether these parameters associated with injuries are a cause or a consequence of the injury. However, some associated parameters could be hypothesized as consequences of the injuries. Our results reported that higher contact time (t_c) was associated with a higher proportion of history of all injury. This is in agreement with results from Mann et al. (2015) reporting increased in running contact time in runners with previous injuries compared to healthy control runners. In addition, we observed that stride length variability (SL_{var}) was associated with the injuries history outcome. An increased stride variability could also be a consequence of lateralized injuries and higher neuro-muscular control to compensate disorder caused by previous injuries (Donoghue et al., 2008).

Specific Injuries According to Specific Pole Vault Biomechanical Patterns

Regression models of history of hamstring and ankle injuries related with biomechanical patterns are presented in **Table 2**. For ankle injuries, the model was not significant ($p = 0.141$) and can explain 35% of the variance, although training per week and speed increased in the last 5 meters were significantly associated with higher proportion of ankle injury history. As discussed previously for all injuries, it seems that higher engagement in pole vault would be associated with higher ankle injury history. For history of hamstring injuries, although there were no significant association, larger inertial loads during high speed running tended to be related to history of hamstring injuries (Chumanov et al., 2011). Higher aerial time reported in our present study could be related with this aspect. Increasing the aerial time would mind increasing the swing phase, and thus potentially the end of the swing phase, which has been reported as associated to hamstring injuries (Chumanov et al., 2011; Kenneally-Dabrowski et al., 2019). The models were not significant, and did not report significant association between biomechanical parameters and history of injuries for hamstring injuries. Moreover, the number of observations were small. Thus, it is therefore impossible to conclude of the association. Nevertheless, we would like to discuss some assumptions regarding these preliminary results in order to provide some perspectives for future researches since the present insignificant results are in agreement with some previous findings. Indeed, Although we reported some differences in pole vault biomechanical parameters between sex, in agreement with previous study (Schade et al., 2004; Cassirame et al., 2017), and age categories, it seems that these latter parameters did not influence the proportion of history of injuries, as shown in the parameters revealed as significant in the regression models.

Methodological Considerations

As strength, this study is the first analyzing biomechanical data together with injury data in pole vault, with the goal of better understanding injury risk factors and mechanics.

Regarding limitation, we can acknowledge the small number of pole vaulters included. However, this was high level pole vaulters (participating in the national championships) and represented 71% of the targeted population. The small sample size lead to a small number of some injury diagnoses (e.g., quadriceps and upper extremity injuries), which did not allow performing regression logistic analyzes. We performed and presented logistic regressions for all secondary outcomes (i.e., hamstring and ankle injuries), although number of observations were small, and logistic regression results showed low R^2 and were not significant. The number of explanatory variables could be considered as too important in comparison to the number of observations. We did not collect anthropomorphic parameters (height and body mass), which would have been of interest to adjust biomechanical parameters. There was a high inter-subject variability in biomechanical parameters, especially in junior. The injury data collection was retrospective leading to the risk of recall bias, and do not allow to determine the cause-consequence relationships regarding the biomechanical pattern and the injury occurrence. Finally, since injury is multifactorial (Bittencourt et al., 2016), other parameters than sex, age category, and pole vault biomechanics should be taken into account to try to reach the optimal approach of injury understanding. All these limitations represent perspectives of future researches, including a prospective data collection of injuries in association with the data collection of biomechanical pole vault parameters, and other parameters which can influence the injury occurrence.

Practical Implications

Pole vault practice is a sport requiring many physical and technical abilities to create and exchange energy with pole to maximize performance (Ekevad and Lundberg, 1997; Frère et al., 2010; Linthorne and Weetman, 2012; Schade and Arampatzis, 2012; Cassirame et al., 2017). During energetic exchange, especially at take-off, many mechanical constraints are applying on musculoskeletal system. Those constraints are generated by the impact and the long force moment from beginning of pole bending until toes off. During this crucial phase for performance (Linthorne, 2000), many parameters (e.g., running speed) are from one side beneficial for performance and in other side potentially harmful. In addition, body position of athlete and pole vault pattern used by the athlete can produce more or less traumatisms.

Therefore, we think that specific attention should be done for each pole vaulter given its specific pole vault pattern. Performance-prevention management should be a win-win strategy based on individual management. Given the importance of the position of the grip (superior) hand at the tack-off related to the risk of injuries, we can suggest at a practical prevention measure to train athletes to increase the angle between the pole and the horizontal axis at the take-off phase. Mastering the transitional phase between the run-up and the take-off phase should also be at the center of training activities. An optimal balance in training volume and intensity (training load) should be found and pole vaulters with high training exposure should be at the center of attention. Finally, the technical training of pole vaulters with previous injuries should be improved by taking attention to potential compensation.

CONCLUSIONS

Our present results reported that one biomechanical parameter related to the take-off phase (lower H2) and some biomechanical parameter related to the terminal phase of the run-up phase (higher Spd, SL_{adj}, SL_{var}, t_c) were significantly associated with higher proportions of all injuries. Although the injury data collection was retrospective leading to the risk of recall bias, and do not allow to determine the cause-consequence relationships regarding the biomechanical patterns and the injury occurrence, this present study is the first to analyze potential association between the biomechanical pole vault patterns and injury occurrence, which is of great help to provide hypotheses/ideas to design future studies and to move forward into prevention measures.

DATA AVAILABILITY

The datasets generated for this study will not be made publicly available because they are included in a preliminary database.

AUTHOR CONTRIBUTIONS

PE and JC conceived, analyzed the data, drafted the manuscript and prepared the table/figure, and designed the study. JC, HS, and SH performed experimentation and data collection. PE, JF, and JC interpreted the results. PE, HS, CB, SH, JF, and JC edited, critically revised the manuscript, and approved the final version.

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A One-Season Prospective Study of Illnesses, Acute, and Overuse Injuries in Elite Youth and Junior Track and Field Athletes

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Background: In high-level adult athletes, injury incidences and characteristics have been reported during international championships and during one season. Youth track and field athletes are also exposed to injury risk, although less information is available on this specific population, as well as on illness risk.

Aim: To determine the prevalence of health problems (i.e., illnesses, acute, and overuse injuries) in high level Youth and Junior Track & Field athletes.

Method: During the 2015–16 athletics season (30 weeks from December 2015 to July 2016), we conducted a prospective cohort study on a population of Youth and Junior Irish national level athletes, during which athletes were asked to complete a weekly web-based questionnaire (Oslo Sports Trauma Research Center questionnaire on health problems) regarding their health problems.

Results: A total of 70 athletes participated (37 male and 33 female athletes), with an average weekly response rate of 71%. The average weekly prevalence for all athletes was 27% (95%CI 17 to 38%) for all health problems, and 11% (95%CI 3 to 18%) for substantial health problems. Average prevalence varied significantly between endurance and explosive disciplines: a higher prevalence of all and substantial health problems and all and substantial overuse injuries was found in endurance disciplines. A higher prevalence of acute injuries was found in explosive disciplines. Characteristics of acute and overuse injuries differed according to sex and discipline: hamstring strain/cramps/spasms was the main injuries in explosive disciplines, and knee tendinopathy and lower leg strain/cramp/spasms in endurance disciplines, trunk cramps/spasms being frequent in both disciplines. Upper respiratory tract problems were the most commonly reported illnesses regardless of sex and disciplines.

Conclusion: This study provides important information regarding the extent of health problem in Youth and Junior track and field athletes. This could help orient injury prevention measures. For injuries, it should be focused on muscle injuries, especially located on the hamstring, calf, and trunk. For illness, prevention measures could include: screening tests for airway problems, but also general illness prevention measures (e.g., drinking regularly, eating "safe" food, regular hand washing, decreasing contact with sick people, avoiding dehydration).

Keywords: epidemiology, track and field, top-level athletes, sports injury prevention, health protection

INTRODUCTION

The practice of track and field (athletics) can lead to a risk of injuries that negatively impact the athlete's participation in sport, daily life and/or physical integrity (Edouard et al., 2011, 2015a). In high-level adult athletes, injury incidences, and characteristics have been reported during international championships (Feddermann-Demont et al., 2014; Edouard et al., 2015b) and during one season (D'Souza, 1994; Bennell and Crossley, 1996; Jacobsson et al., 2013). Youth track and field athletes are also exposed to injury risk, although less information is available on this specific population (Watson and Dimartino, 1987; D'Souza, 1994; Edouard et al., 2012; Jacobsson et al., 2012, 2013). High-level youth athletes are potentially exposed to high training load (intensity and volume) and competition pressure. However, to our knowledge, only two studies reported results on the injury rates and characteristics in youth high-level athletics (Jacobsson et al., 2012, 2013). The only prospective study to consider this specific population found the proportion of injured athletes was similar to that of adult athletes (e.g., ≈60%), while injury characteristics differed (Jacobsson et al., 2013). There is thus a need for increasing the knowledge on this specific population, given (i) the lack of data available (Steffen and Engebretsen, 2010), (ii) the need for age specific data, as results from adult studies cannot be extrapolated to this population, (iii) to examine the health benefits/risk profile of high-level athletics practice in youth athletes (e.g., injuries and their potential long-term sequelae; Moseid et al., 2018), and (iv) to guide injury prevention strategies.

Illness also represents a health problem that could be caused by sport participation (i.e., heat-related or gastro-enteritis problems; Pluim et al., 2016; Moseid et al., 2018; Edouard et al., 2019), can also increase the risk of subsequent injuries (Timpka et al., 2017), and lead to a decrease in sport participation or performance. Therefore, when talking about athletes' health, it is of interest to also collect such data to have a more complete view of health issues. Hence, to our knowledge, no data has been published in youth track and field athletes, although previously reported in elite junior Tennis (Pluim et al., 2016), and in a cohort of youth elite athletes from several sports (Moseid et al., 2018).

In this context, the aim of the study was to determine the prevalence of injuries and illnesses in high level Youth and Junior track and field athletes.

METHODS

Study Design

During the 2015–16 athletics season (from December 2015 to July 2016), we conducted a prospective cohort study on a population of Youth and Junior national level track and field athletes from the Athletics Ireland High Performance Programme (Athletics Ireland Athlete Carding Scheme (AIACS), http://www.athleticsireland.ie/high-performance/carding/). During the 30-week period, athletes were asked to complete a weekly web-based questionnaire regarding their health conditions. The study was approved by the Saint-Etienne University Hospital Ethical Committee (IORG0004981).

Population

At the beginning of the 2015–16 athletics season, Athletics Ireland (http://www.athleticsireland.ie) provided the main investigator (PC) a list of Youth (Under 18) and Junior (Under 20) level athletes (aged from 16 to 19 years) who had obtained performances of a sufficient standard to qualify them for AIACS. The AIACS selection process requires athletes to achieve set performance criteria stated within a selection policy to be considered for membership to the programme.

All the athletes on the AIACS, and their parents when minors, were invited by email to participate in the injury and illness surveillance study. Athlete consent (and parental consent when athletes were minors) for the survey and the data being used for both surveillance and research purposes was obtained upon admission to the Carding Scheme. Athletes were included if they were registered with Athletics Ireland, had no contraindication for athletics participation, appeared on the list of the AIACS, consented to participate, were able to read and reply to questions in English, and had suitable internet access.

Data Collection Procedure

At the beginning of the 2015–16 athletics season, baseline data (i.e., sex, age, and discipline) was collected. Disciplines were then grouped into explosive disciplines (sprints, hurdles, throws, jumps, combined events) and endurance disciplines (middle and long distance running, race walking) (Timpka et al., 2017).

During the 30 weeks of the surveillance study, all injury, and illness were recorded by the Athletics Ireland Physiotherapist responsible for the group (PC). An email was sent to all included athletes at the start of each week, with a link to complete an online questionnaire (SurveyMonkeyInc, San

Mateo, California, USA). If the questionnaire was not completed, an automated reminder was sent after 24 h and then 48 h after the initial email. The Oslo Sports Trauma Research Center questionnaire on health problems was used to collect data (Clarsen et al., 2013, 2014), which includes four questions on the consequences of health problems on sports participation, training volume, sports performance, and perceived pain. This questionnaire and methods have been reported to be used with success in population of youth athletes in elite junior tennis (Pluim et al., 2016), in adolescent elite orienteerers (Von Rosen et al., 2016), in youth football players (Leppänen et al., 2019), in junior handball players (Aasheim et al., 2018), and in youth elite athletes in multiple sports (Moseid et al., 2018), and appears of interest in sports who have limited access to medical personnel (e.g., athletics; Edouard et al., 2014; Leppänen et al., 2019). Questionnaire responses were reviewed and collated on a weekly basis by the Athletics Ireland Physiotherapist. If the athlete answered the minimum score for each question (full participation without problems/no training reduction/no performance reduction/no symptoms) no further action was taken. If the athlete reported anything other than the minimum value for any question, follow-up was carried out by email, telephone or consultation by the Athletics Ireland Physiotherapist. Using this information, the Athletics Ireland Physiotherapist classified each problem as an illness, acute injury, or overuse injury.

In accordance with the classification system described in the consensus statement for epidemiological studies in athletics (Timpka et al., 2014), health problems were classified as injuries if they were disorders of the musculoskeletal system or concussions, and as illnesses if they involved other body systems such as (but not limited to) the respiratory system, the digestive system and the neurological system, as well as non-specific/generalized, psychological and social problems. Injuries were further categorized into acute and overuse injuries: acute injuries were defined as those whose onset could be linked to specific injury event, whereas overuse injuries were those that could not be linked to a clearly identifiable event (Fuller et al., 2006; Jacobsson et al., 2013). All these classifications were made by the Athletics Ireland Physiotherapist based on the interview and/or physical examination when needed. For all forms of health problems, substantial problems were defined as those leading to moderate or severe reductions in training volume, or moderate or severe reductions in sports performance, or complete inability to participate in sport (i.e., problems where athletes selected option 3, 4, or 5 in either Question 2 or 3). Injuries and illnesses were classified according to locations, types, and severities as described in the consensus statement for epidemiological studies in athletics (Timpka et al., 2014). Locations were grouped into head, trunk, upper extremity, and were detailed for the lower extremity. Diagnoses were the combination of location and type for each injury.

According to Clarsen et al. (2013), in cases where the same diagnosis was interspersed with periods of apparent recovery an effort was made to determine if the cases were exacerbations of unresolved problems or recurrences of fully recovered problems. Illnesses were treated in a similar fashion with repeated episodes of chronic conditions treated as a single case for the purposes of analysis. Data collected in the first week were not included in the summary measures, as per previous recommendations (Clarsen et al., 2013).

Statistical Analysis

Means and corresponding standard deviations (SD) were calculated for baseline demographics. Potential differences in baseline demographics between male and female athletes and between endurance and explosive disciplines were tested with t-tests for continuous variables and Chi^2 statistics for dichotomous variables.

The response rate was calculated for each week by dividing the number of responders by the number of included athletes, and averaged for the whole study period.

The proportion of athletes presenting with at least one health problem was calculated for all health problems, and separately for illness, acute and overuse injury. Comparisons were performed between (i) female *vs.* male athletes (male being the reference) and (ii) explosive vs. endurance disciplines (explosive being the reference) for athletes' proportion using relative risk (RR) with 95%CI.

According to Clarsen et al. (2014), prevalence measures were calculated for all and substantial health problems, illnesses, injuries, overuse injuries and acute injuries for each week that the project was conducted. This was performed by dividing the number of athletes reporting any form of problem by the number of questionnaire respondents. All prevalence measures were presented as averages, with 95% confidence intervals (95% CI). Characteristics of health problems were presented using descriptive analysis (as frequencies). Comparisons of the average prevalence and of the health problem characteristics were then made between (i) female vs. male athletes and (ii) endurance vs. explosive disciplines using Chi^2-tests and Bonferroni correction was used to control for multiple tests. Data were processed using Excel software. Significance was accepted at $p < 0.05$.

RESULTS

Population

Among the 76 athletes selected and listed for being members of the Athletics Ireland's High Performance Carding System, six athletes declined to participate. A total of 70 (92%) athletes gave their consent and were included in the present study at the start the 2015–16 athletics season (December 1, 2015), consisting of 37 male and 33 female athletes, without significant sex-related differences in the mean age and athletics disciplines distribution (**Table 1**). The distribution of all the 70 athletes in disciplines was:

- In male athletes: middle distance (18.6%), long distance (7.1%) or race walking (1.4%) for endurance disciplines, and sprints (14.3%), hurdles (2.9%), jumps (1.4%), throws (5.7%), or combined events (1.4%) for explosive disciplines;
- In female athletes: middle distance (5.7%), long distance (2.9%) or race walking (0.0%) for endurance disciplines; and

TABLE 1 | Number (percentage) of athletes included in the study, and number (percentage) of athletes presenting at least one health problem during the 30-week study period according to sex and discipline groups.

	All athletes						Male athletes						Female athletes					
	Total		Endurance		Explosive		Total		Endurance		Explosive		Total		Endurance		Explosive	
Athletes																		
n (% of all athletes)	70	(100.0)	25	(35.7)	45	(64.3)	37	(52.9)	19	(27.1)	18	(25.7)	33	(47.1)	6	(8.6)	27	(38.6)
Age (mean (SD))	17.1	(0.8)	17.3	(0.7)	16.9	(0.9)	17.2	(0.8)	17.3	(0.7)	17.1	(0.9)	16.9	(0.8)	17.3	(0.5)	16.8	(0.9)
Athletes with at least one health problem [n (%)]																		
All health problems	61	(87.1)	18	(72.0)	43	(95.6)	30	(81.1)	13	(68.4)	17	(94.4)	31	(93.9)	5	(83.3)	26	(96.3)
Illness	42	(60.0)	11	(44.0)	31	(68.9)	18	(48.6)	8	(42.1)	10	(55.6)	24	(72.7)	3	(50.0)	21	(77.8)
Injury	54	(77.1)	17	(68.0)	37	(82.2)	28	(75.7)	12	(63.2)	16	(88.9)	26	(78.8)	5	(83.3)	21	(77.8)
Acute injury	31	(44.3)	7	(28.0)	24	(53.3)	16	(43.2)	6	(31.6)	10	(55.6)	15	(45.5)	1	(16.7)	14	(51.9)
Overuse injury	37	(52.9)	13	(52.0)	24	(53.3)	19	(51.4)	9	(47.4)	10	(55.6)	18	(54.5)	4	(66.7)	14	(51.9)

sprints (17.1%), hurdles (7.1%), jumps (2.9%), throws (8.6%), combined events (2.9%) for explosive disciplines.

There were no significant differences between male and female athletes in mean age ($p > 0.05$) and in the distribution of athletics disciplines (Chi2 = 9.4; $p > 0.05$).

Over the 30-week period, the average weekly response rate to the health questionnaires was 71.3 ± 11.6 %, without significant differences with regards to sex and disciplines (**Table 2** and **Figure 1**). The individual response rate range from 0 to 100% over the 30-week period: 53 (76%) athletes had a response rate higher than 50%, including 17 (24%) athletes completed all the requested questionnaires (response rate = 100%) and 21 (30%) athletes between 85 and 99% (note that two male athletes replied only to the first questionnaire).

Among the 70 included athletes, 61 (87.1%) presented with at least one health problem during the 30-week period: 60.0% ($n = 42$) at least one illness, 44.3% ($n = 31$) at least one acute injury, and 52.9% ($n = 37$) at least one overuse injury (**Table 1**). From these 61 athletes, 13.1% of athletes presented with only one health problem, 26.2% two, 19.7% three, 21.3% four, 16.4% five, and 1.6% six and seven health problems during the study period.

The proportion of athletes was significantly higher in female than male athletes for health problems (RR = 1.27, 95% CI 1.11 to 1.47) and for illnesses (RR = 1.64, 95% CI 1.13 to 2.40); we reported no other sex-related differences for acute and overuse injuries, or in endurance and explosive disciplines (**Table 1**).

The proportion of athletes with all health problems was significantly higher in explosive than endurance disciplines for all the 70 athletes (RR = 1.33, 95% CI 1.03 to 1.71); we reported no other discipline-related differences for illnesses, acute and overuse injuries and in male and female athletes (**Table 1**).

Prevalence of Health Problems

The average weekly prevalence for all athletes was 27.3% (95% CI 16.9 to 37.8%) for all health problems, and 10.6% (95% CI 3.4 to 17.8%) for substantial health problems (**Table 2** and **Figure 2**).

The average weekly prevalence of all and substantial health problems, illness, injuries, acute injuries, and overuse injuries did not significantly vary between male and female athletes when considering all and explosive disciplines. However, in considering endurance disciplines alone, there was a significant difference between male and female athletes for all health problems, injuries, overuse injuries, and substantial overuse injuries ($p < 0.0001$; **Table 2** and **Figure 2**).

The average weekly prevalence of all and substantial health problems, injuries, acute injuries and overuse injuries significantly varied between endurance and explosive disciplines, while not for illnesses and substantial acute injuries (**Table 2** and **Figure 2**).

Illnesses

A total of 74 illnesses were reported by 42 athletes. 52.4% presented with one illness, 26.2% two, 14.3% three and 7.1% four illnesses. The proportion of athletes with at least one illness was significantly higher in female than male athletes (RR = 1.64, 95% CI 1.13 to 2.40), without other sex-related or discipline-related differences (**Table 1**).

The average weekly prevalence of illnesses and substantial illnesses was not significantly different between sex and disciplines (**Table 2**).

Most reported illnesses affected the upper respiratory tract (73.0%), and led to 1 week (68.9%), or between 2 or 3 weeks of absence in sport (31.1%) (**Table 3**).

Acute Injuries

A total of 47 acute injuries were reported by 31 athletes. 58.1% presented with one acute injury, 35.5% two, 3.2% three and 3.2% four acute injuries. The proportion of athletes with at least one acute injury did not significantly vary according to sex or discipline (**Table 1**).

The average weekly prevalence of acute injuries was significantly higher in explosive than endurance disciplines for all and female athletes ($p < 0.002$), while not for male athletes, and did not significantly vary between sex (**Table 2**). The average weekly prevalence of substantial acute injuries did not significantly vary between sex and disciplines (**Table 2**).

Most reported acute injuries were located at the trunk (19.1%), the hamstring (17.1%) or the knee (17.1%), affected muscles

TABLE 2 | Average weekly prevalence (with 95% confidence intervals) during the 30-week observation period of all health problems and substantial health problems reported, as well as for subcategories of illness, acute and overuse injury in each subgroup of sex and disciplines.

	All athletes			Male athletes			Female athletes		
	Total	Endurance	Explosive	Total	Endurance	Explosive	Total	Endurance	Explosive
Athletes [n (%)]	70 (100.0)	25 (35.7)	45 (64.3)	37 (52.9)	19 (27.1)	18 (25.7)	33 (47.1)	6 (8.6)	27 (38.6)
Response rate [mean (SD)]	71.3 (11.6)	64.4 (12.5)	75.1 (11.6)	69.2 (11.6)	63.0 (13.3)	75.9 (10.4)	73.6 (12.5)	69.0 (15.3)	74.6 (13.4)
All health problems	27.3 (16.9 to 37.8)	32.7 (21.7 to 43.7)*	24.7 (14.6 to 34.9)*	25.6 (15.4 to 35.8)	27.4 (16.9 to 37.8)[$]	24.2 (14.2 to 34.2)	29.0 (18.4 to 39.6)	47.1 (35.4 to 58.8)[$]*	25.2 (15.0 to 13.0)*
Illness	6.8 (0.9 to 12.7)	6.9 (0.9 to 12.8)	6.8 (0.9 to 12.7)	5.6 (0.2 to 11.0)	5.8 (0.3 to 11.2)	5.6 (0.2 to 11.0)	8.0 (1.6 to 14.3)	8.9 (2.2 to 15.5)	7.6 (1.4 to 13.9)
Injury	20.5 (11.0 to 30.0)	25.9 (15.6 to 36.1)*	17.9 (8.9 to 26.9)*	20.0 (10.6 to 29.3)	21.6 (12.0 to 31.3)[$]	18.6 (9.5 to 27.7)	21.0 (11.5 to 30.6)	38.3 (26.9 to 49.7)[$]*	17.5 (8.6 to 26.5)*
Acute injury	7.5 (1.3 to 13.7)	4.3 (−0.5 to 9.0)*	9.0 (2.3 to 15.7)*	7.5 (1.3 to 13.6)	5.5 (0.1 to 10.8)	9.3 (2.5 to 16.1)	7.4 (1.3 to 13.6)	0.9 (−1.3 to 3.0)*	8.8 (2.2 to 15.5)*
Overuse injury	13.0 (5.1 to 20.9)	21.6 (12.0 to 31.2)*	9.0 (2.3 to 15.6)*	12.5 (4.8 to 20.3)	16.2 (7.5 to 24.8)[$]*	9.3 (2.5 to 16.1)*	13.6 (5.6 to 21.6)	37.4 (26.1 to 48.7)[$]*	3.9 (−0.6 to 8.4)*
Substantial health problems	10.6 (3.4 to 17.8)	17.6 (8.7 to 26.6)*	7.4 (1.3 to 13.5)*	11.3 (3.9 to 18.7)	15.6 (7.1 to 24.1)*	8.0 (1.6 to 14.3)*	9.8 (2.8 to 16.8)	22.8 (13.0 to 32.6)*	7.0 (1.0 to 13.0)*
Illness	2.1 (−1.3 to 5.4)	2.1 (−1.3 to 5.4)	2.1 (−1.3 to 5.5)	2.2 (−1.2 to 5.7)	1.8 (−1.3 to 5.0)	2.7 (−1.1 to 6.6)	1.9 (−1.3 to 5.1)	2.6 (−1.1 to 6.3)	1.8 (−1.3 to 4.8)
Injury	8.4 (1.9 to 14.9)	15.4 (6.9 to 23.8)*	5.1 (0.0 to 10.3)*	9.2 (2.4 to 15.9)	13.6 (5.5 to 21.6)*	5.6 (0.2 to 11.0)*	7.5 (1.3 to 13.7)	20.2 (10.8 to 29.6)*	4.8 (−0.2 to 9.8)*
Acute injury	3.4 (−0.9 to 7.6)	2.6 (−1.1 to 6.3)	3.7 (−0.7 to 8.2)	3.5 (−0.8 to 7.7)	3.5 (−0.8 to 7.8)	3.5 (−0.8 to 7.8)	3.2 (−0.9 to 7.3)	0.0 (0.0 to 0.0)	3.9 (−0.6 to 8.4)
Overuse injury	5.0 (−0.1 to 10.1)	12.8 (5.0 to 20.7)*	1.4 (−1.4 to 4.2)*	5.7 (0.3 to 11.2)	10.1 (3.0 to 17.1)[$]*	2.1 (−1.3 to 5.5)*	4.3 (−0.4 to 9.1)	20.2 (10.8 to 29.6)[$]*	0.9 (−1.3 to 3.1)*

[$] *Significant difference between male and female athletes.*
**Significant difference between endurance and explosive disciplines.*

(61.7%), or ligamentous structures (14.9%), and led to one week of absence in sport (46.8%) (**Table 4**).

The main injury diagnoses of acute injuries were lower leg strain/tear in male endurance athletes (25%), trunk muscle cramps/spasms in female endurance athletes (100%, corresponding to the only one acute injury for female endurance athletes) and male explosive athletes (31.6%), and hamstring strain/tear in female explosive athletes (21.1%).

Overuse Injuries

A total of 70 overuse injuries were reported by 37 athletes. 48.6% presented with one overuse injury, 29.7% two, 5.4% three, and 16.2% four overuse injuries. The proportion of athletes with at least one overuse injury did not significantly vary according to sex or discipline (**Table 1**).

The average weekly prevalence of overuse injuries and substantial overuse injuries was significantly higher in female than male athletes for endurance disciplines ($p < 0.0001$), and higher in endurance disciplines when compared to explosive disciplines for all, male and female athletes ($p < 0.001$; **Table 2**).

Most reported overuse injuries were located at the hamstring (25.7%), the posterior lower leg (15.7%) or the foot (14.3%), in most cases affected muscles (64.3%), and led to 1 week of absence from sport (57.1%) (**Table 4**).

The main injury diagnoses of overuse injuries were knee tendinopathy in male endurance athletes (29.4%), lower leg muscle cramps in female endurance athletes (28.6%), and hamstring muscle cramps/spasms in both male explosive athletes (40.0%) and female explosive athletes (21.1%).

DISCUSSION

The main findings of the present study were that (1) almost ninety percent of Youth and Junior Track & Field (athletics) athletes presented with at least one health problem during the season: 60% an illness and 77% an injury; (2) for an average week, almost one third of Youth and Junior athletes presented with a health problem, and 11% a substantial health problem; (3) average prevalence varied significantly between endurance and explosive disciplines: higher prevalence of health problems and overuse injuries in endurance disciplines, and higher prevalence of acute injuries in explosive disciplines; (4) upper respiratory tract problems were the most commonly reported illnesses regardless of sex and disciplines; and (5) characteristics of acute and overuse injuries differed according to sex, discipline and injury type: trunk, hamstring and lower leg muscle injuries being the most commonly reported injuries. Such information is of great interest to better understand health problems in athletes and to help direct injury and illness prevention strategies (van Mechelen et al., 1992; Jacobsson et al., 2013; Edouard et al., 2015a).

Our present study confirms that Youth and Junior track and field athletes present a risk of sustaining a health problem, since almost all included athletes have presented with at least one health problem during the season (only nine athletes reported being fully healthy for the duration of the study). Moreover, health problems represent a part of an athlete's daily life since

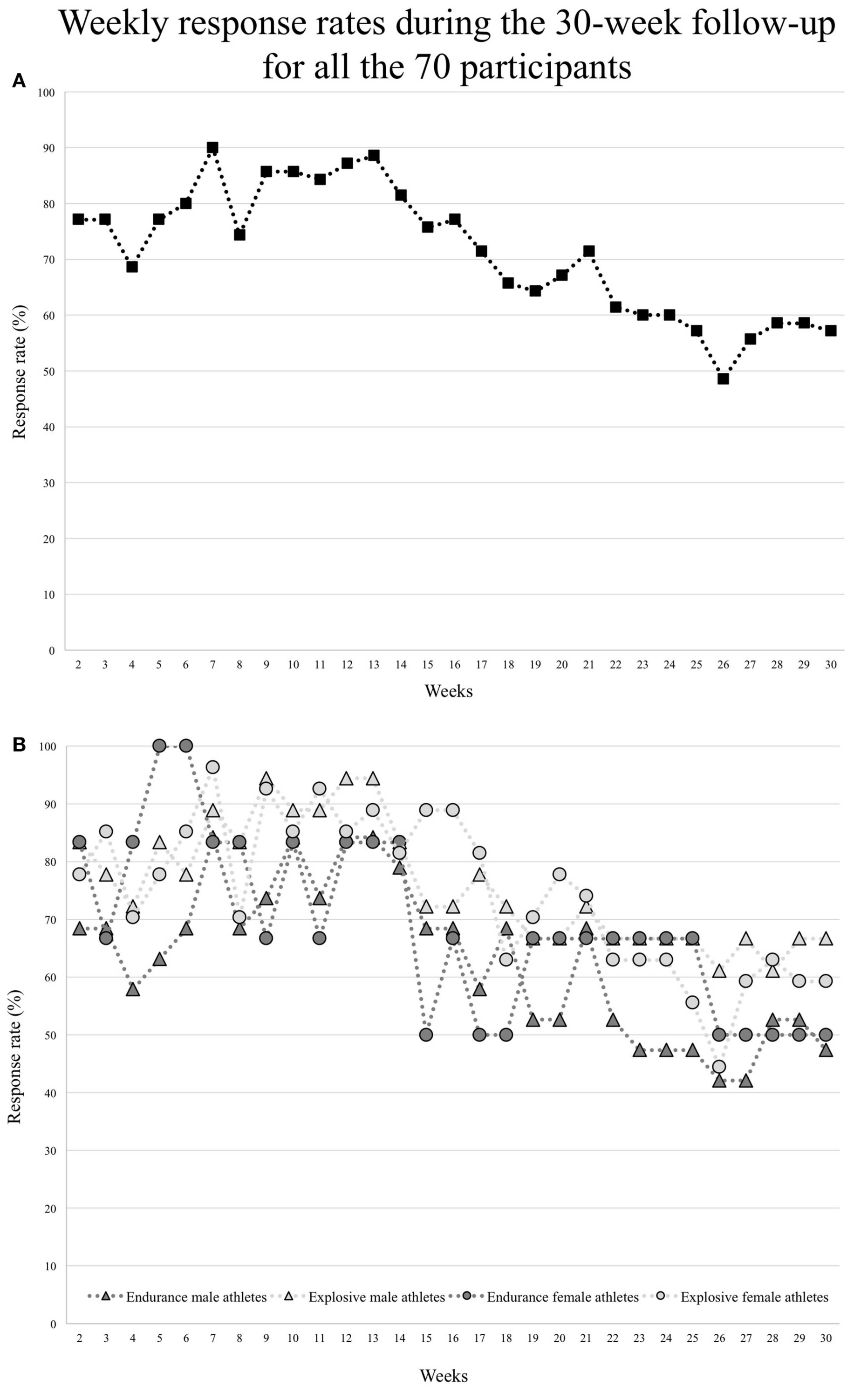

FIGURE 1 | Weekly response rates during the 30-week follow-up for **(A)** all the 70 participants, and for **(B)** endurance and explosive male and female athletes separately.

on average approximately one third of Youth and Junior athletes reported having at least one health problem each week. This is in agreement with previous studies in other sports reported in similar age-category population using the same methodology (Pluim et al., 2016; Moseid et al., 2018). A mean weekly prevalence of health problems of 21 and 43% have been reported

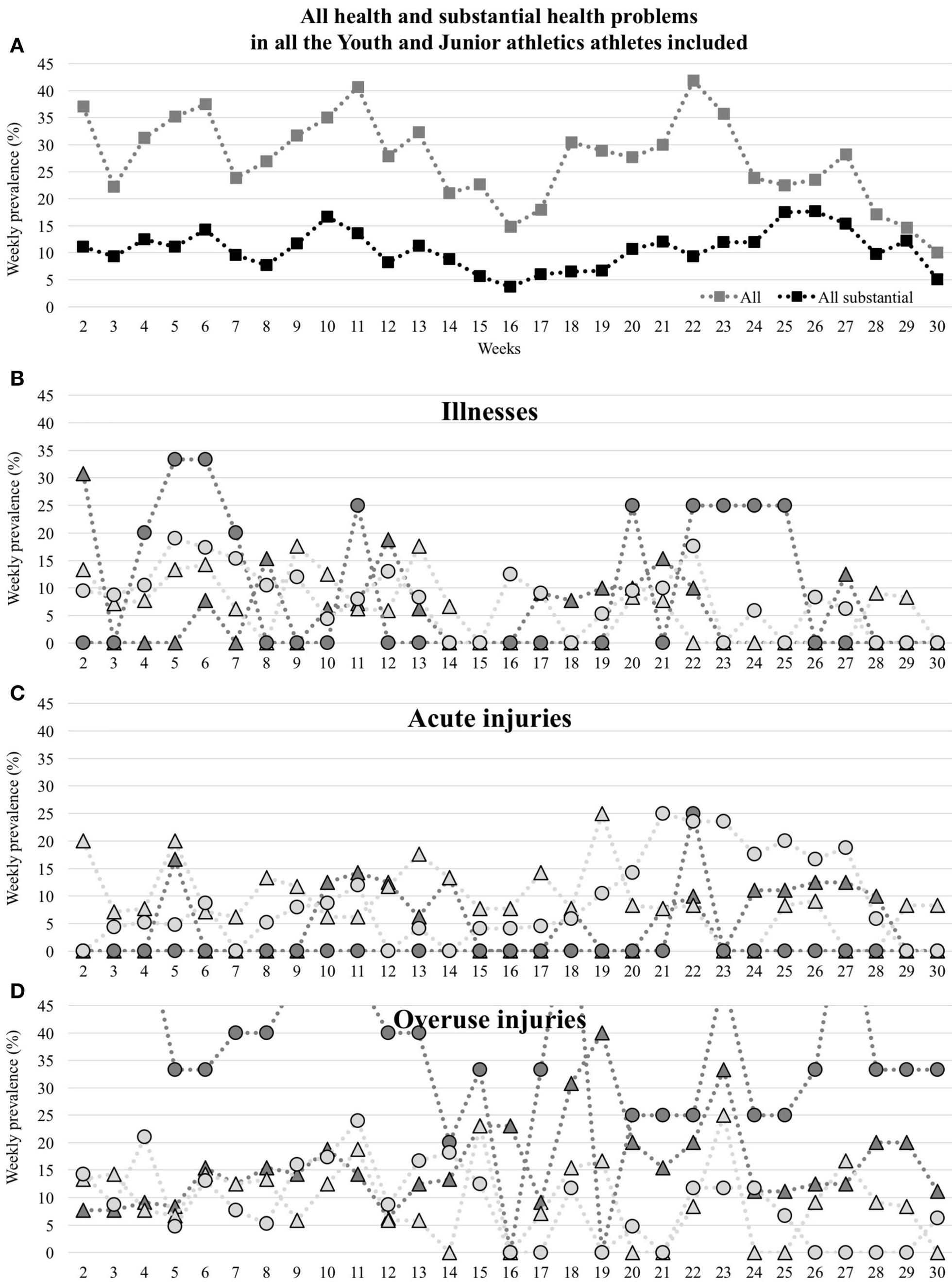

FIGURE 2 | Weekly prevalence of health problems [all and substantial health problems **(A)**, illnesses **(B)**, acute injuries **(C)** and overuse injuries **(D)**] reported during the 30-week follow-up period.

in Dutch Junior Tennis players (Pluim et al., 2016) and in high level Norway athletes (Moseid et al., 2018), respectively. These values in Youth and Junior athletes are also comparable to those reported in adults in Norwegian Olympic level athletes (36%) (across a variety of sports) (Clarsen et al., 2013). These results reveal that health problems are frequent in such population of young athletes. This raises some questions about their future: Do these problems lead to stopping sport? What are the negative consequences of these rates of injury and illness? This is an issue that needs to be addressed. Efforts should be made to develop

TABLE 3 | Characteristics of reported illnesses (results are presented in percentage of illnesses per categories of sex and discipline).

	All athletes			Male athletes			Female athletes		
	Total $n = 74$	Endurance $n = 22$	Explosive $n = 52$	Total $n = 30$	Endurance $n = 15$	Explosive $n = 15$	Total $n = 44$	Endurance $n = 7$	Explosive $n = 37$
Affected system									
Upper respiratory tract	73.0	81.8	69.2	73.3	86.7	60.0	72.7	71.4	73.0
Lower respiratory tract	9.5	4.5	11.5	6.7	6.7	6.7	11.4	0.0	13.5
Gastrointestinal	10.8	9.1	11.5	16.7	6.7	26.7	6.8	14.3	5.4
Urogenital/Gynecological	2.7	4.5	1.9	0.0	0.0	0.0	4.5	14.3	2.7
Neurological	1.4	0.0	1.9	0.0	0.0	0.0	2.3	0.0	2.7
Ophtalmological/Otological	2.7	0.0	3.8	3.3	0.0	6.7	2.3	0.0	2.7
Severity									
Minor	68.9	68.2	69.2	66.7	73.3	60.0	70.5	57.1	73.0
Moderate	31.1	31.8	30.8	33.3	26.7	40.0	29.5	42.9	27.0
Severe	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

better understanding of the extent of the problems through epidemiological studies, and to limit this risk by preventive measures evaluated through interventional studies.

We reported no sex-related differences in the average prevalence across all health problems (except for endurance disciplines). This is in contrast with results from several different sports in youth elite athletes reporting higher health problems in girls, probably caused by higher illness prevalence (Moseid et al., 2018). In agreement with the latter result, we reported that the proportion of athletes with health problems was significantly higher in female than male athletes. This difference was probably due to the significant higher proportion of female athletes with at least one illness. Hence, this could suggest a predisposition of youth female athletes to illnesses, and especially urogenital/gynecological problems as reported in our study, and in agreement with Edouard et al. (2019). It is therefore necessary for medical teams to make provision to manage these conditions and to develop preventive measures.

An average weekly prevalence of illness of 6.8% was reported in our study, which is in agreement with results reported in Dutch Junior Tennis players (5.8%) (Pluim et al., 2016) and slightly lower than in high-level Norwegian athletes (12%) (Moseid et al., 2018). Reported illness problems were comparable with those reported in Tennis (Pluim et al., 2016): upper respiratory tract infections being the most common problem. This is also in agreement with previous study on elite adult athletes during the context of international athletics championships (Edouard et al., 2019). Strategies for prevention of upper respiratory tract infections is a priority target in athletics.

Our results reported discipline-related differences in average prevalence of health problems. Specifically a higher prevalence of all and substantial health problems and all and substantial overuse injuries in endurance disciplines, which differed from Moseid et al. (2018) reporting no differences. We also reported higher prevalence of acute injuries in explosive disciplines, which is consistent with results from Moseid et al. (2018) These results suggest that disciplines with different physical, mechanical, technical and psychological demands (Edouard et al., 2011, 2015a,b; Feddermann-Demont et al., 2014), lead to different constraints, and consequently to different injury characteristics, with acute injuries being more frequent in explosive disciplines and overuse in endurance disciplines.

Although using differing methodology, our results were similar to those from Jacobsson et al. (2013) in terms of injury proportion, proportion of overuse injuries, and injury location and type. Hamstring strains/cramps/spasms were the main injuries in athletes participating in explosive disciplines, as previously reported in youth athletes (Edouard et al., 2012; Jacobsson et al., 2013; Opar et al., 2014), and in high-level adult athletes during international athletics championships (Edouard et al., 2016). This is probably due to the important role of hamstring muscles in sprint acceleration performance (Morin et al., 2015), which makes these muscles at high risk of injury in explosive disciplines. This clearly makes hamstring injury an important target for injury prevention in athletics (Edouard et al., 2016). As Jacobsson et al. (2013), we reported few stress fractures (1.7% of all injuries), and only in endurance female athletes, in contrast with Bennell and Crossley (1996). This could be due to misdiagnosis, better prevention, or study design (e.g., Bennell and Crossley, 1996) focused their study on stress fractures).

Overuse injuries represented the health problem with the highest average weekly prevalence, in comparison to acute injuries and illnesses. This is consistent with previous findings in youth athletes and from other sports: 78% orienteers (Von Rosen et al., 2016), 47% in tennis (Pluim et al., 2016), 37% in elite Norwegian young athletes. This reinforces the need for using a surveillance system capable of capturing overuse injuries (Bahr, 2009; Clarsen et al., 2013, 2014; Pluim et al., 2016), to better understand these problem and how to prevent them.

The first strength of the study is providing data on injuries and illnesses in young athletes practicing athletics, given the lack of data in this field (Jacobsson et al., 2013; Edouard et al., 2015a). In addition, the current study is, to the best of our knowledge,

TABLE 4 | Characteristics of reported acute and overuse injuries [results are presented in numbers (percentage)].

	All athletes					Male athletes							Female athletes						
	Total	Endurance athletes		Explosive athletes		Total	Endurance male athletes			Explosive male athletes			Total	Endurance female athletes			Explosive female athletes		
	Total	Acute	Overuse	Acute	Overuse	Total	Total	Acute	Overuse	Total	Acute	Overuse	Total	Total	Acute	Overuse	Total	Acute	Overuse
TOTAL	**117 (100.0)**	**9 (100.0)**	**24 (100.0)**	**38 (100.0)**	**46 (100.0)**	**64 (100.0)**	**25 (100.0)**	**8 (100.0)**	**17 (100.0)**	**39 (100.0)**	**19 (100.0)**	**20 (100.0)**	**53 (100.0)**	**8 (100.0)**	**1 (100.0)**	**7 (100.0)**	**45 (100.0)**	**19 (100.0)**	**26 (100.0)**
LOCATION																			
Head	1 (0.9)	0 (0.0)	0 (0.0)	1 (2.6)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (1.9)	0 (0.0)	0 (0.0)	0 (0.0)	1 (2.2)	1 (5.3)	0 (0.0)
Trunk	15 (12.8)	1 (11.1)	0 (0.0)	8 (21.1)	6 (13.0)	9 (14.1)	0 (0.0)	0 (0.0)	0 (0.0)	9 (23.1)	6 (31.6)	3 (15.0)	6 (11.3)	1 (12.5)	1 (100.0)	0 (0.0)	5 (11.1)	2 (10.5)	3 (11.5)
Upper extremity	9 (7.7)	1 (11.1)	0 (0.0)	3 (7.9)	5 (10.9)	7 (10.9)	1 (4.0)	1 (12.5)	0 (0.0)	6 (15.4)	3 (15.8)	3 (15.0)	2 (3.8)	0 (0.0)	0 (0.0)	0 (0.0)	2 (4.4)	0 (0.0)	2 (7.7)
Pelvic/Hip/Groin	12 (10.3)	1 (11.1)	4 (16.7)	4 (10.5)	3 (6.5)	5 (7.8)	2 (8.0)	1 (12.5)	1 (5.9)	3 (7.7)	2 (10.5)	1 (5.0)	7 (13.2)	3 (37.5)	0 (0.0)	3 (42.9)	4 (8.9)	2 (10.5)	2 (7.7)
Quadriceps	5 (4.3)	0 (0.0)	0 (0.0)	3 (7.9)	2 (4.3)	2 (3.1)	0 (0.0)	0 (0.0)	0 (0.0)	2 (5.1)	0 (0.0)	2 (10.0)	3 (5.7)	0 (0.0)	0 (0.0)	0 (0.0)	3 (6.7)	3 (15.8)	0 (0.0)
Hamstrings	26 (22.2)	1 (11.1)	2 (8.3)	7 (18.4)	16 (34.8)	14 (21.9)	3 (12.0)	1 (12.5)	2 (11.8)	11 (28.2)	3 (15.8)	8 (40.0)	12 (22.6)	0 (0.0)	0 (0.0)	0 (0.0)	12 (26.7)	4 (21.1)	8 (30.8)
Knee	14 (12.0)	2 (22.2)	6 (25.0)	6 (15.8)	0 (0.0)	10 (15.6)	7 (28.0)	2 (25.0)	5 (29.4)	3 (7.7)	3 (15.8)	0 (0.0)	4 (7.5)	1 (12.5)	0 (0.0)	1 (14.3)	3 (6.7)	3 (15.8)	0 (0.0)
Anterior lower leg	5 (4.3)	0 (0.0)	3 (12.5)	0 (0.0)	2 (4.3)	4 (6.3)	3 (12.0)	0 (0.0)	3 (17.6)	1 (2.6)	0 (0.0)	1 (5.0)	1 (1.9)	0 (0.0)	0 (0.0)	0 (0.0)	1 (2.2)	0 (0.0)	1 (3.8)
Posterior lower leg	16 (13.7)	2 (22.2)	3 (12.5)	3 (7.9)	8 (17.4)	5 (7.8)	3 (12.0)	2 (25.0)	1 (5.9)	2 (5.1)	0 (0.0)	2 (10.0)	11 (20.8)	2 (25.0)	0 (0.0)	2 (28.6)	9 (20.0)	3 (15.8)	6 (23.1)
Ankle (lateral)	2 (1.7)	0 (0.0)	0 (0.0)	2 (5.3)	0 (0.0)	1 (1.6)	0 (0.0)	0 (0.0)	0 (0.0)	1 (2.6)	1 (5.3)	0 (0.0)	1 (1.9)	0 (0.0)	0 (0.0)	0 (0.0)	1 (2.2)	1 (5.3)	0 (0.0)
Foot	12 (10.3)	1 (11.1)	6 (25.0)	1 (2.6)	4 (8.7)	7 (10.9)	6 (24.0)	1 (12.5)	5 (29.4)	1 (2.6)	1 (5.3)	0 (0.0)	5 (9.4)	1 (12.5)	0 (0.0)	1 (14.3)	4 (8.9)	0 (0.0)	4 (15.4)
TYPE																			
Concussion	1 (0.9)	0 (0.0)	0 (0.0)	1 (2.6)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (1.9)	0 (0.0)	0 (0.0)	0 (0.0)	1 (2.2)	1 (5.3)	0 (0.0)
Stress fracture	2 (1.7)	0 (0.0)	2 (8.3)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	2 (3.8)	2 (25.0)	0 (0.0)	2 (28.6)	0 (0.0)	0 (0.0)	0 (0.0)
Other bone injuries	9 (7.7)	1 (11.1)	3 (12.5)	1 (2.6)	4 (8.7)	5 (7.8)	4 (16.0)	1 (12.5)	3 (17.6)	1 (2.6)	1 (5.3)	0 (0.0)	4 (7.5)	0 (0.0)	0 (0.0)	0 (0.0)	4 (8.9)	0 (0.0)	4 (15.4)
Ligmanetous injuries	9 (7.7)	0 (0.0)	1 (4.2)	7 (18.4)	1 (2.2)	5 (7.8)	1 (4.0)	0 (0.0)	1 (5.9)	4 (10.3)	3 (15.8)	1 (5.0)	4 (7.5)	0 (0.0)	0 (0.0)	0 (0.0)	4 (8.9)	4 (21.1)	0 (0.0)
Meniscus/cartilage	3 (2.6)	0 (0.0)	0 (0.0)	2 (5.3)	1 (2.2)	1 (1.6)	0 (0.0)	0 (0.0)	0 (0.0)	1 (2.6)	1 (5.3)	0 (0.0)	2 (3.8)	0 (0.0)	0 (0.0)	0 (0.0)	2 (4.4)	1 (5.3)	1 (3.8)
Muscle strain/tear	15 (12.8)	4 (44.4)	0 (0.0)	11 (28.9)	0 (0.0)	8 (12.5)	4 (16.0)	4 (50.0)	0 (0.0)	4 (10.3)	4 (21.1)	0 (0.0)	7 (13.2)	0 (0.0)	0 (0.0)	0 (0.0)	7 (15.6)	7 (36.8)	0 (0.0)
Muscle cramps	59 (50.4)	2 (22.2)	8 (33.3)	12 (31.6)	37 (80.4)	30 (46.9)	5 (20.0)	1 (12.5)	4 (23.5)	25 (64.1)	8 (42.1)	17 (85.0)	29 (54.7)	5 (62.5)	1 (100.0)	4 (57.1)	24 (53.3)	4 (21.1)	20 (76.9)
Tendinosis/tendinopathy/ aponeurosis	15 (12.8)	1 (11.1)	10 (41.7)	2 (5.3)	2 (4.3)	12 (18.8)	10 (40.0)	1 (12.5)	9 (52.9)	2 (5.1)	1 (5.3)	1 (5.0)	3 (5.7)	1 (12.5)	0 (0.0)	1 (14.3)	2 (4.4)	1 (5.3)	1 (3.8)
Arthritis/synovitis/bursitis/ impignement	4 (3.4)	1 (11.1)	0 (0.0)	2 (5.3)	1 (2.2)	3 (4.7)	1 (4.0)	1 (12.5)	0 (0.0)	2 (5.1)	1 (5.3)	1 (5.0)	1 (1.9)	0 (0.0)	0 (0.0)	0 (0.0)	1 (2.2)	1 (5.3)	0 (0.0)
SEVERITY																			
Minor	62 (53.0)	5 (55.6)	14 (58.3)	17 (44.7)	26 (56.5)	34 (53.1)	15 (60.0)	4 (50.0)	11 (64.7)	19 (48.7)	8 (42.1)	11 (55.0)	28 (52.8)	4 (50.0)	1 (100.0)	3 (42.9)	24 (53.3)	9 (47.4)	15 (57.7)
Moderate	36 (30.8)	1 (11.1)	6 (25.0)	12 (31.6)	17 (37.0)	21 (32.8)	6 (24.0)	1 (12.5)	5 (29.4)	15 (38.5)	8 (42.1)	7 (35.0)	15 (28.3)	1 (12.5)	0 (0.0)	1 (14.3)	14 (31.1)	4 (21.1)	10 (38.5)
Severe	19 (16.2)	3 (33.3)	4 (16.7)	9 (23.7)	3 (6.5)	9 (14.1)	4 (16.0)	3 (37.5)	1 (5.9)	5 (12.8)	3 (15.8)	2 (10.0)	10 (18.9)	3 (37.5)	0 (0.0)	3 (42.9)	7 (15.6)	6 (31.6)	1 (3.8)

For all athletes, there was a significant difference between acute and overuse injuries in the distribution of injury type (Chi2 = 40.9; $p < 0.0001$), but not for location and type.

the first study using the OSTRC Questionnaire to monitor injury and illness prevalence in high level Youth & Junior level track and field athletes. Indeed, we used an epidemiological methodology which takes into account the limits of the traditional "time loss" model (Bahr, 2009; Clarsen et al., 2013, 2014; Pluim et al., 2016). Then, in an individual sport like Athletics, in which data collection is a challenge (Edouard et al., 2014), almost all the targeted population participated in the study (92%) and a high response rate was sustained throughout.

Some limitations related to the data collection methods have been previously discussed (Clarsen et al., 2014; Pluim et al., 2016; Von Rosen et al., 2016; Aasheim et al., 2018; Moseid et al., 2018), it is however of interest to acknowledge them again. Since the data was reported directly by the athletes (athlete's self-reports), the quality of the data depends on their will and time, in addition to other parameters influencing self-reported data collection (Jacobsson et al., 2013; Clarsen et al., 2014; Pluim et al., 2016; Von Rosen et al., 2016; Aasheim et al., 2018; Moseid et al., 2018). Athletes can sometimes report as injury a "normal" pain related to the athletics practice, or as illness a "transient" problem (e.g., dizziness, tiredness, etc.; Pluim et al., 2016; Aasheim et al., 2018; Moseid et al., 2018). In order to limit this bias, the Athletics Ireland Physiotherapist checked and classified each health problem, and this is why we also used the "substantial problem" definition, which filters out the least consequential problems and may provide a better estimate of the impact of injuries and illnesses on athletes' health (Moseid et al., 2018). Some could have omitted or minimized their health problems, because they feared that this would have consequences for their selection in the national team. Athletes' self-reports are also dependent on both high responses rates throughout the course of the study. In the present study, the average response rate decreased as the season progressed (≈25% decrease from week 2 to week 30), without rupture at a specific period. This has also previously been reported, and it seems of great interest to better understand why the response rate decreased, for instance: Did the athletes find it boring to answer the questionnaire and did not see any interest in them? Were there explanations related to the sport: they did not want their medical information to be known at the proximity of important competitions for fear of not being selected…? Then, measures should be found to limit this missing data source leading to potential bias. No athlete was excluded because of "recurrent" missing data, which can represent a limit. Most of the data was self-reported data, limited objective data was collected, and no anthropometric data (Jacobsson et al., 2013). The questionnaire used in the present study (Oslo Sports Trauma Research Center questionnaire) has been developed and validate for use in adult athletes (Clarsen et al., 2013, 2014), and not for use in Youth athletes, which could represent a limitation (Pluim et al., 2016). However, it has previously been used with success in population of youth athletes in elite junior tennis (Pluim et al., 2016), in adolescent elite orienteers (Von Rosen et al., 2016), in youth football players (Leppänen et al., 2019), in junior handball players (Aasheim et al., 2018), and in youth elite athletes in multiple sports (Moseid et al., 2018), and appears of interest in sports who have limited access to medical personnel (e.g., athletics; Edouard et al., 2014; Leppänen et al., 2019), and the present study population aged from 16 to 18 which are close to adults. A recall bias could lead to bias (Moseid et al., 2018), although asking on health problem occurred during the previous week aimed to limit this bias. No exposure data was collected (training and competition duration and intensity), which could have been of interest to better understand injury risk. We did not analyse subsequent or recurrent health problems. No power calculations were performed to establish the size of the study population as a basis for statistical testing, since we aimed to reach the entire population defined elite track and field athletes in Ireland.

The relatively high prevalence of health problems in this group of Youth and Junior track and field athletes is a cause for concern.

Prevention is key and can be done through education of athletes and all their stakeholders (coaches, parents, medical teams, athlete's caregivers; Jacobsson et al., 2018). Education programmes should take into account the knowledge of targeted audiences and characteristics of health problems being addressed (Jacobsson et al., 2018; Rodríguez-serrano et al., 2018). Stakeholders should pay attention and not neglect athletes' complaints of pain or fatigue, and where appropriate early care of health problems should be facilitated (including a clear diagnosis and an optimized treatment/care or rehabilitation). All key stakeholders should be involved in the development of primary prevention interventions (Jacobsson et al., 2013; Pluim et al., 2016).

For illness, prevention measures could include: screening tests for airway problems, but also general illness prevention measures (including but not restricted to; Engebretsen et al., 2010; Hanstad et al., 2011; Alonso et al., 2012; Périard et al., 2017; Timpka et al., 2017; Moseid et al., 2018): drinking regularly and only "safe" water, eating only "safe" food, regular hand washing, decreasing contact with sick people, avoiding dehydration & heat stress, and increasing uptake of vaccinations. Time should be spent on developing adolescent-adapted education resources, focused on eating, sleeping, social media, and screen time.

For injuries, prevention measures should be focused on muscle injuries, especially located on the hamstring, calf and trunk, by general strengthening/stretching programmes, screening athletes at risk, and providing individualized deficiency-based programmes. Efforts should also be made to better understand the risk factors and mechanisms of these main injuries to develop/improve prevention measures.

CONCLUSIONS

This study provides important information regarding the extent of health problem in Youth and Junior track and field athletes. Almost all Youth and Junior athletes presented at least one health problem during the season, and almost a third a health problem at each time of the season. Hamstring, trunk, and lower leg muscle injuries were the most frequent reported injuries, and upper respiratory tract problems the most frequently reported illnesses. These results could help orient injury and illness prevention strategies in Youth and Junior athletes toward these main injuries.

DATA AVAILABILITY

The datasets analyzed in this manuscript are not publicly available. Requests to access the datasets should be directed to paulcarragher@instituteofsport.ie.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the study was approved by the Saint-Etienne University Hospital Ethical Committee (IORG0004981). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

PC conceived, designed the study, and performed data collection. PC, AR, and PE analyzed the data, interpreted the results and edited, critically revised the manuscript, and approved the final version. PC and PE drafted the manuscript and prepared the table/figure.

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Differences in the Force Velocity Mechanical Profile and the Effectiveness of Force Application During Sprint-Acceleration Between Sprinters and Hurdlers

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This cross-sectional study aimed to compare the horizontal and vertical force-velocity profile between female sprinters and hurdlers. Twelve high-level athletes (6 sprinters and 6 hurdlers) participated in this investigation. The testing procedures consisted of two maximal 40-m sprints and five to six vertical jumps with additional loads. For the sprint-acceleration performance, the velocity-time data, recorded by a high-speed camera, was used to calculate the variables of the horizontal F-V profile (theoretical maximal values of force [$HZT\text{-}F_0$], velocity [$HZT\text{-}V_0$], power [*HZT-Pmax*], the proportion of the theoretical maximal effectiveness of force application in the antero-posterior direction [*RFmax*], and the rate of decrease in the ratio of horizontal force [*DRF*]). The best trial of each vertical jumping condition, obtained by an optical measurement system, was used to determine the components of the vertical F-V profile (theoretical maximal values of force [$VTC\text{-}F_0$], velocity [$VTC\text{-}V_0$], and power [*VTC-Pmax*]). The female sprinters showed higher statistical differences for *HZT-Pmax* (2.46 ± 0.67, $d = 2.1$, $p = 0.004$), $HZT\text{-}V_0$ (0.45 ± 0.18, $d = 1.4$, $p = 0.03$), and *RFmax%* ($2.9 \pm 0.9\%$, $d = 1.8$, $p = 0.01$) than female hurdlers. No statistical differences were observed for $HZT\text{-}F_0$ (0.69 ± 0.3, $d = 1.15$, $p = 0.07$), *DRF%* ($-0.24 \pm 0.4\%$, $d = 0.3$, $p = 0.62$), $VTC\text{-}F_0$ (-2.1 ± 3.8, $d = 0.3$, $p = 0.59$), $VTC\text{-}V_0$ (0.25 ± 0.31, $d = 0.5$, $p = 0.45$), and *VTC-Pmax* (1.75 ± 2.5, $d = 0.4$, $p = 0.5$). Female sprinters are able to apply higher horizontally-oriented forces onto the ground during the acceleration phase than female hurdlers.

Keywords: force-velocity profile, ratio of force application, sprint performance, sprint mechanics, biomechanics of hurdling

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INTRODUCTION

Sprinting is a cyclic locomotion depended on the mechanical forces produced through the action of the neuromuscular system. During sprint running, the lower limbs have to produce high forces in order to accelerate, and sustain high running speeds (Bret et al., 2002). The purpose of sprint running performance is to cover a required distance in the shortest time. On the other side, the purpose of sprint-hurdle running performance is to successfully cover a required distance in as short time as possible while clearing barriers. In both events, during the acceleration phase, athletes try to generate high levels of horizontal ground-reaction force (GRF), and apply it with effectiveness onto the ground, despite increasing velocity (Morin et al., 2011). A new macroscopic inverse dynamics approach, based on kinematics and kinetics parameters of the runner's body center of mass during sprint-acceleration (horizontal profile) and ballistic push-off movements (vertical profile), can determinate the force-velocity (F-V), and power-velocity (P-V) relationships, and the mechanical effectiveness of force application parameters (Morin and Samozino, 2016). The horizontal force-velocity-power (F-V-P) profile is described by the theoretical maximal values of force (*HZT-*F_0), velocity (*HZT-*V_0), and power (*HZT-Pmax*), the proportion of the theoretical maximal effectiveness of force application in the anterior-posterior direction (*RFmax in %*) and the rate of decrease in the ratio of horizontal force as the velocity increases over the entire acceleration phase (*DRF in %* $s{\cdot}m^{-1}$). The vertical F-V-P profile corresponds with the theoretical maximal values of force (*VTC-*F_0), velocity (*VTC-*V_0), and power (*VTC-Pmax*). The horizontal and vertical profiles allow to accurately evaluate force, velocity and power developed by lower limbs during sprint running acceleration and loaded squat jumps (SJ) (Morin and Samozino, 2016). Both horizontal and vertical F-V-P profile could provide a deeper insight into the maximal mechanical properties and function of the lower-body muscles. The horizontal F-V-P profile provides information for the specific sprint-acceleration motion, while the vertical F-V-P profile provides information for the maximal levels of force, and velocity of the neuromuscular system (Morin and Samozino, 2016). The F-V-P profile is able to distinguish differences in the mechanical properties of athletes from different sports, levels of practice, playing positions, age, and sex (Buchheit et al., 2014; Cross et al., 2015; Slawinski et al., 2017; Alcazar et al., 2018; Jiménez-Reyes et al., 2018a,b; Haugen et al., 2019).

It is known that high-level sprinters are able to apply high forward-oriented forces onto the supporting ground during the acceleration phase (Weyand et al., 2000; Kugler and Janshen, 2010; Morin et al., 2011; Otsuka et al., 2014; Nagahara et al., 2018). This ability seems to be more important for sprint performance than the total amount of force they are able to produce (Morin et al., 2011). The horizontal component of the GRF and the mechanical effectiveness of force application were significantly correlated to 100-m performance from non-specialists to elite sprinters (Morin et al., 2012). The higher amount of horizontal GRF in sprint-acceleration performance depends on the higher activation and the torque production capability of the hip extensors muscles (Morin et al., 2015). High-level sprinters should produce high amount of force in the anterior-posterior direction and minimize forces in all other directions (lateral and vertical) in order to reach the maximum velocity. If the total horizontal force created during ground contact is positive, horizontal velocity increases. As sprinters reach their maximal velocity, the ground contact duration gets shorter at each step, and the overall orientation gets more vertically-oriented, which is related to an overall progressive vertical orientation of the GRF vector at each support phase (Nagahara et al., 2018). In the hurdle race the athletes must produce great amount of horizontal velocity and maintain it while approaching, and clearing the barriers and running between them. The maximal horizontal velocity that a hurdler can produce depends on the amount of effective force that he can apply during ground contact, throughout the race (Čoh and Iskra, 2012). It would be interesting to examine the mechanical characteristics of top national athletes from the two events where speed is the requirement but with different technical characteristics (i.e., differences in trunk angle during the acceleration phase and maximum speed phase decides hurdle clearance). Would high-level sprinters show a different vertical and horizontal mechanical profile from top high-level hurdlers? It has been proposed that the vertical profile could provide information regarding the maximal level of force and velocity of the athlete's neuromuscular system, whereas horizontal profiling could provide information as to the specific sprint acceleration motion and especially the ability to effectively apply force during sprinting (Morin and Samozino, 2016; Jiménez-Reyes et al., 2018b). For this purpose, the horizontal and vertical force-velocity-power (F-V-P) profile between female sprinters and hurdlers were compared. We hypothesized that sprinters would present higher overall mechanical output capabilities *(HTZ-Pmax)* in the forward direction, higher ability to develop horizontal force at high velocities *(HTZ-*V_0*)*, higher ability to produce horizontal force during sprint-acceleration *(HTZ-*F_0*)*, and greater maximal effectiveness of force application *(RFmax)*, than hurdlers.

MATERIALS AND METHODS

Participants

12 high-level female athletes, 6 sprinters (Mean ± SD: age 23.5 ± 3.0 years; stature 1.67 ± 0.07 m; weight 60.1 ± 2.0 kg; personal best in 100-m sprint running performance 11.76 ± 0.2 s), and 6 hurdlers (age 21.0 ± 5.1 years; stature 1.68 ± 0.05 m; weight 59.2 ± 4.6 kg; personal best in 100-m hurdles running performance 14.06 ± 0.3 s) who participated in the finals of their events during the national championship, gave their written informed consent to participate in this study, which was approved by the local ethical committee, and conducted in accordance with the Declaration of Helsinki. No participants reported physical limitations, health problems or musculoskeletal injuries that could compromise testing. Participants were required to refrain from vigorous exercise for 2 days before testing. The tests were conducted over 2 different testing sessions, within the same week, in an indoor stadium and during the competitive athletes' period.

Testing Procedure

All sessions began with a specific sprint warm-up that involved a 10 min of low-pace running, followed by 5 min of lower limb muscle dynamic stretching, 5 min of sprint-specific drills, and three progressive 40-m sprints separated by 2 min of passive rest (Jiménez-Reyes et al., 2018a). At the first testing session, each athlete performed two maximal sprints of 40-m from a three-point crouching position with 5 min of rest between each trial. The velocity-time data of each sprint was recorded by a high-speed camera (Casio Exilim EX-F1, Tokyo, Japan) sampling at

300 Hz. The high-speed camera was fixed on a tripod, 10-m away from the runway at the half of sprinting distance (i.e., 20-m) and at a height of 1-m corresponding approximately to the height of athlete's center of mass. The video parallax error was corrected to ensure the different split times are measured properly when athletes cross the different targeted distances (5, 10, 15, 20, 25, 30, 35, and 40-m) (Romero-Franco et al., 2017).

At the second testing session, the push-off distance was calculated as the difference between lower limb length (distance from great trochanter to tip of the toes with extended lower limps) and starting height at the squat jump (vertical distance from greater trochanter to ground). Each subject performed vertical maximal SJ without loads and with progressively increasing, five to six, extra loads ranging from 10 to 60 kg. The starting position was self-selected by the participants before the trial and was kept fixed for the subsequent trials using a marker on the squat cage to maintain the same squat depth throughout the experiment (Giroux et al., 2015). The participants were asked to maintain their starting position for about 1–2 s and then apply force as fast as possible and jump for maximum height. Participants kept their arms on their hips for jumps without load and on the bar for loaded jumps. Two valid trials were performed with each load with 3 min of recovery between trials. Jump heights were obtained by using an optical measurement system (OptoJump Next Microgate, Bolzano, Italy).

Data Processing

The sprint velocity-time video data was analyzed by Kinovea (v.0.8.15) and the best trial was used to determine the components of the horizontal mechanical F-V profile (*HZT-F_0, HZT-V_0, HZT-Pmax, RFmax, DRF*). The acceleration of the athlete's center of mass to the antero-posterior direction can be calculated from the changes in running velocity over time and net horizontal GRF can be calculated by considering the body's center of mass of the athlete and aerodynamic friction of force (Samozino et al., 2016). The entire force-velocity relationship represents the maximal theoretical horizontal force that the lower limbs could produce over one contact at a null velocity (*HZT-F_0*) and the theoretical maximum velocity that could be produced during a support phase in the absence of mechanical constraints (*HTZ-V_0*). These variables were calculated as extrapolated from the linear sprint F–V relationship, as the intercept of the x-(force) and y-(velocity) axis of the linear regressions. Multiplying horizontal F and V values for each support phase, the equivalent of maximal mechanical power output *(HTZ-Pmax)* in the forward direction is obtained and computed as $Pmax = F_0 \times V_0/4$. The ratio of force *(RF)* was calculated as the ratio of the horizontally-oriented component to the total GRF, computed as $RF = FHzt/Ftot$. The Rate of decrease in *RF* (*DRF*) computed as the slope of the linear RF–V relationship, as the velocity increases until the end of the acceleration. The parameters derived with this method have been validated compared to force plate measurements and a low absolute bias (≤6%) was found while a high reliability (coefficients of variation (CV) and standard errors of measurement <5%) was observed as well (Samozino et al., 2016; Morin et al., 2019). For the vertical F-V profile, the best trial of each jumping condition was used to determine the components of the mechanical F-V profile *(VTC-F_0. VTC-V_0, VTC-Pmax)*, according to the Samozino's method. This method is based on the fundamental principles of dynamics applied to the body center of mass during a vertical jump and on the analysis of its mechanical energy at different specific instants of the movement (Samozino et al., 2008). The force-axis intercept of the F-V relationship (*VTC-F_0*) represents the maximal external force lower limbs could produce during a theoretical extension movement at null velocity. The velocity-axis intercept (*VTC-V_0*) corresponds to the maximal velocity at which lower limbs could extend during a theoretical extension under zero load. The apex of the P-V relationships *(VTC-Pmax)* is the maximal power output lower limbs can produce over one extension and computed as $Pmax = F_0 \times V_0/4$ (Samozino et al., 2013; Jaric, 2016; Morin and Samozino, 2016). A high reliability (ICCs: 0.96–0.99 and CVs: 2.7–8.4%) and validity (absolute bias < 3%, Pearson correlation coefficients: 0.88–0.98, CVs: 4–15%) of this method compared to force plate measurements for the estimation of force, velocity and power during jumping trials has been reported (Samozino et al., 2008; Giroux et al., 2015).

Statistical Analysis

Data are presented as Means ± standard deviation (SD). Normality (Shapiro-Wilk test) and homogeneity of variance (Levene test) were checked before analyses. Independent samples *t*-tests were used to compare the horizontal (*HTZ-F_0, HTZ-V_0, HTZ-Pmax, RFmax, DRF*), and the vertical (*VTC-F_0, VTC-V_0, VTC-Pmax*) mechanical F-V-P profiles between sprinters, and hurdlers. The magnitude of the differences was also expressed as a standardized mean difference with the corresponding 95% confidence interval. The criteria to interpret the magnitude of the ES [Cohen's d effect size [ES]] was as follows: small (d = 0.2), medium (d = 0.5), and large ($d \geq 0.8$) (Cohen, 2013). All statistical analyses were performed using the software package SPSS (IBM SPSS version 25.0, Chicago, IL, USA), and statistical significance was set at an alpha level of 0.05.

RESULTS

The descriptive data of the horizontal and vertical mechanical F-V profile are shown in **Table 1**. Regarding the mechanical parameters during sprinting, there were significant differences between the female sprinters and hurdlers for HZT-Pmax (t = 3.67, $p = 0.004$, $d = 2.1$), HZT-V_0 ($t = 2.46$, $p = 0.03$, $d = 1.4$) (**Figure 1**), and RFmax% ($t = 3.1$, $p = 0.01$, $d = 1.8$) (**Figure 2**) which were higher for the sprint athletes, while HZT-F_0 ($t = 2.0$, $p = 0.07$, $d = 1.15$) tended to be higher for the sprint athletes and no differences were found in DRF% ($t = -0.5$, $p = 0.62$, $d = 0.3$). Regarding the mechanical parameters during the vertical squat jump trial, no differences were found between groups for VTC-F_0 ($t = 0.55$, $p = 0.5$, $d = 0.3$), VTC-V_0 ($t = 0.78$, $p >= 0.45$, d = 0.5) (**Figure 3**), and VTC-Pmax ($t = 0.7$, $p = 0.5$, $d = 0.4$).

DISCUSSION

The present study explored the mechanical properties and function of the lower-body through the F-V approach between

TABLE 1 | Descriptive data presented as mean ± standard deviation (SD), 95% confidence intervals, mean difference ± (SD), and 95% confidence intervals of the difference of the horizontal and vertical mechanical force-velocity profile displayed by event.

	Mean (SD)	95% CI	Mean Difference (SD)	95% CI of the Difference
HZT-F_0 ($N \cdot kg^{-1}$)				
Sprinters	7.68 ± 0.45	7.21–8.15	0.69 ± 0.4	0.08–1.47
Hurdlers	6.99 ± 0.72	6.23–7.75		
HZT-V_0 ($m \cdot s^{-1}$)				
Sprinters	**9.37 ± 0.22***	9.13–9.60	**0.45 ± 0.18***	0.04–0.86
Hurdlers	**8.91 ± 0.39**	8.50–9.32		
HZT-Pmax ($W \cdot kg^{-1}$)				
Sprinters	**18.0 ± 1.12***	16.8–19.2	**2.46 ± 0.6***	0.97–3.96
Hurdlers	**15.5 ± 1.20**	14.3–16.8		
RFmax (%)				
Sprinters	**45.7 ± 1.27***	44.3–47.0	**2.9 ± 0.9***	0.8–4.9
Hurdlers	**42.8 ± 1.86**	40.9–44.8		
DRF (%)				
Sprinters	−7.62 ± 0.48	−8.12– −7.12	−0.24 ± 0.4	−1.28–0.8
Hurdlers	−7.38 ± 0.10	−8.48– −6.29		
VTC- F_0 ($N \cdot kg^{-1}$)				
Sprinters	39.2 ± 6.91	31.9–46.4	−2.1 ± 3.8	−10.6–6.45
Hurdlers	41.3 ± 6.36	34.6–47.9		
VTC-V_0 ($m \cdot s^{-1}$)				
Sprinters	2.81 ± 0.69	2.08–3.53	0.25 ± 0.1	−0.45–0.96
Hurdlers	2.56 ± 0.35	2.19–2.93		
VTC-Pmax ($W \cdot kg^{-1}$)				
Sprinters	26.9 ± 5.09	21.6–32.3	1.75 ± 2.5	−3.83–7.33
Hurdlers	25.2 ± 3.40	21.6–28.8		

*HZT-F_0, theoretical maximal horizontal force; HZT-V_0, theoretical maximal horizontal velocity; HZT-Pmax, theoretical maximal horizontal power; RFmax, ratio of the horizontally-oriented component to the total ground reaction force; DRF, rate of decrease in ratio of force with increasing speed during sprint acceleration; VTC-F_0, theoretical maximal vertical force; VTC-V_0, theoretical maximal vertical velocity; VTC-Pmax, theoretical maximal vertical power. *Significant differences from hurdlers (highlighted in bold): $P < 0.05$.*

high-level female sprinters and hurdlers. Supporting our hypothesis, sprinters were able to apply higher forward-oriented forces onto the ground during the acceleration phase and develop higher power outputs (*HZT-F_0, RFmax, HZT-V_0, HZT-Pmax*) than hurdlers with the magnitude of these differences being large.

The theoretical maximal velocity *(HZT-V_0)* shows that female sprinters can keep producing horizontal force at higher velocities, which reflects a higher capability of lower limb to produce horizontal force at fast running speeds. This is also reflected in the fact that female sprinters have higher overall mechanical power output capabilities *(HZT-Pmax)* during the acceleration phase than female hurdlers. The ratio of force *(RF)* corresponds the ability to effectively orient the horizontal force at the first steps of the acceleration phase in relation to the total force produced. Female sprinters can apply more effectively the force developed by the lower limbs at low velocities, than hurdlers. It should be noted that *RF* is quantified by the first steps of the acceleration and is less representative of the entire acceleration phase. The ability to orient total force in the horizontal direction at each step to overall sprint acceleration phase *(DRF)* does not differ between female sprinters and hurdlers. Differences in the technique requirements between the events might be a reason for the differences in the mechanical abilities observed during sprinting between the two groups of athletes. In comparison to the technique requirements for the sprint start and the acceleration phase in short sprint events, the athletes of short sprint hurdles events after clearing the blocks tend to show a progressive increase in trunk angle at both touchdown and toe-off (Walker et al., 2019). The progression in trunk angle indicates a transition from the block start toward high velocity running, by producing a slightly larger total body vertical emphasis while allowing the trunk to extend more for the preparation into the first barrier (Walker et al., 2019). It can be hypothesized that through repetitive training hurdlers could adopt this technique while sprinting regardless of the presence of hurdles barriers affecting their ability to effectively apply the force onto the ground. This is in agreement with Kugler and Janshen (2010) who found that the further forward oriented ground reaction forces during acceleration, come together with further forward oriented body positions. However, it has to be mentioned that it is unknown whether specific hurdling training leads to the adoption of this specific technique while sprinting, regardless of the presence of hurdles barriers affecting so, their ability to effectively apply the force onto the ground. The present results also suggest

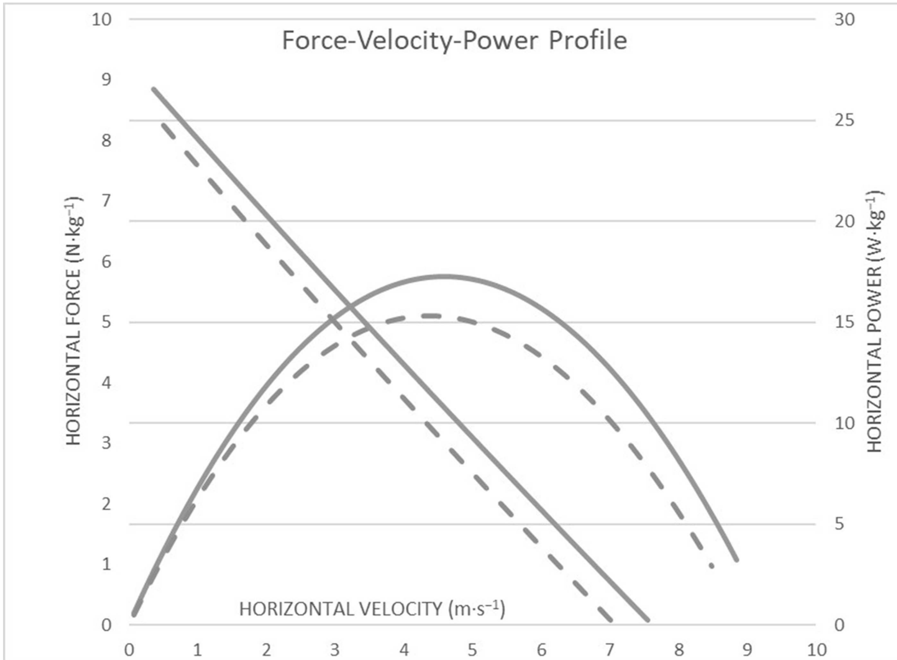

FIGURE 1 | Graphic representation of the relationship between force-velocity and power-velocity as profiled from a 40-m sprint testing procedure between high-level female sprinters (black line) and hurdlers (dashed line). HZT-F_0 and HZT-V_0 represent the y and x intercepts of the linear regression, and the theoretical maximum of force, and velocity able to be produced in the absence of their opposing unit. HZT-Pmax represents the maximum power produced, determined as the peak of the polynomial fit between power and velocity.

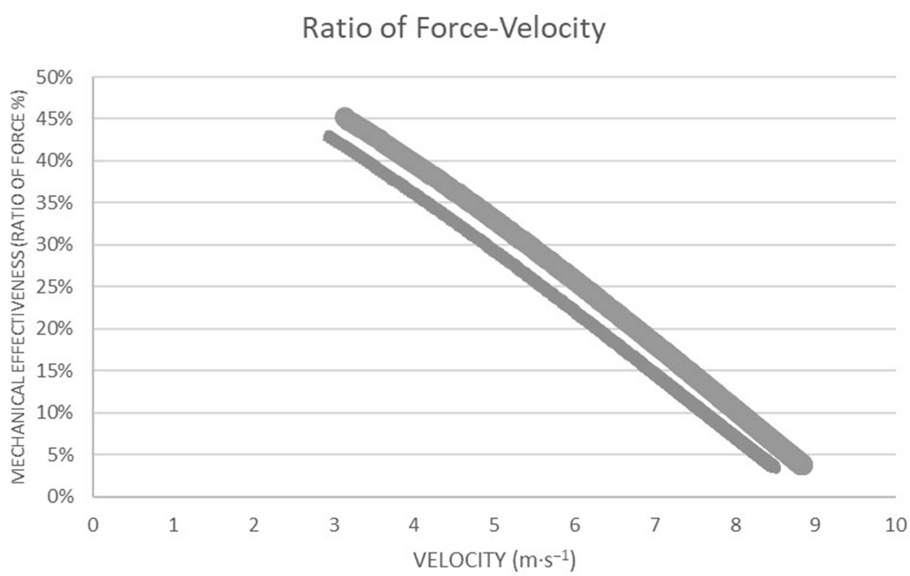

FIGURE 2 | Graphic representation of the Ratio of Force as a function of running velocity during a sprint testing procedure for high-level female sprinters (weighted line) and hurdlers (thin line) and the decrease in the Ratio of Force as velocity increases.

that the ability to develop horizontal force during sprinting is not related with the ability of lower limbs to produce force, as obtained during jumping testing procedure, reflecting the lower limb neuromuscular properties. Nevertheless, in high-level to elite populations, horizontal force production during sprinting acceleration is likely less determined by the neuromuscular system capability to produce total force onto the ground as assessed through the vertical F-V-P profile.

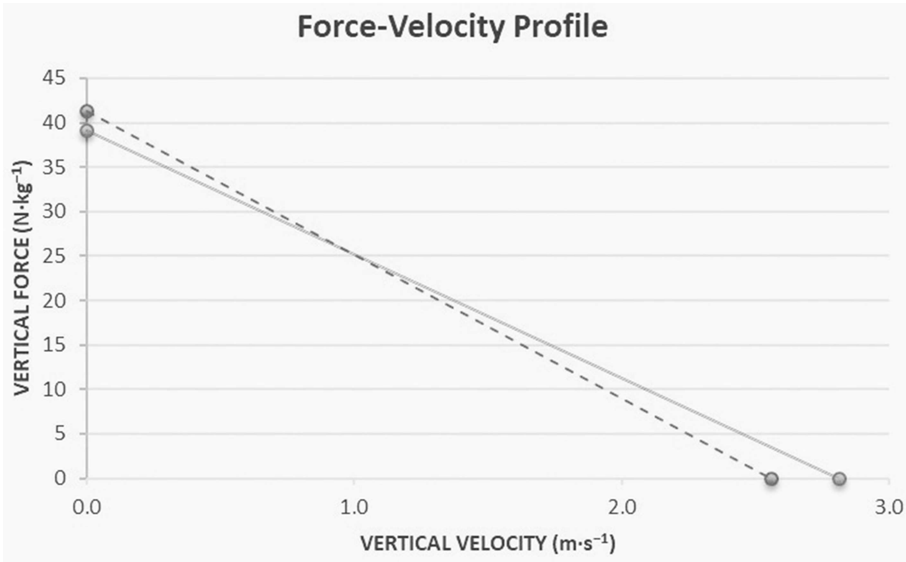

FIGURE 3 | Graphic representation of the relationship between force-velocity as profiled from the vertical jumps with additional loads testing procedure between high-level female sprinters (solid line) and hurdlers (dashed line). VTC-F_0 represent the maximal external force lower limbs could produce during a theoretical extension movement at null velocity; VTC-V_0 represent to the maximal velocity at which lower limbs could extend during a theoretical extension under zero load.

The differences in sprinting acceleration performance between sprinters and hurdlers may be more explained by differences in the mechanical effectiveness of force application between the events and especially by the ability to apply more effectively the force into the anteroposterior direction. These results are in agreement with previous studies that have revealed that high-level athletes are able to horizontally apply higher forces upon contact with the ground (Morin et al., 2011; Buchheit et al., 2014; Kawamori et al., 2014; Pantoja et al., 2016; Jiménez-Reyes et al., 2018b).

To our knowledge, this is the only study exploring the differences in horizontal and vertical F-V-P profile between high-level female sprinters and hurdlers during the competitive period of the season. The F-V-P approach is expected to be useful for both researchers and coaches in order to ensure a more specific, accurate, and comprehensive characterization of athletes' physical qualities toward better designed training programs. It will be of practical importance for track and field coaches to focus their training into improving the horizontal components of F-V-P profile, especially for the high-level female hurdlers. Females hurdlers clearing lower barrier heights, compared to men's 110-m hurdles event, and possibly, a specific training in order to achieve higher forward orientation of the produced force in the initial acceleration run could be leading into performance maximization. In addition, coaches should monitor their horizontal, and vertical FVP profile throughout the season in order to give emphasis in the components that each athlete should improve. Future research should investigate the differences in mechanical capabilities, the effectiveness of force application as well as to examine the kinetics and kinematics parameters to better understand the mechanisms behind the differences of the sprint-acceleration performance between high-level sprinters and hurdlers in order to design effective training programs.

The study has some limitations that must be addressed. The sample size of the present study is small and may reduce statistical power and increase the margin of error, which can affect the results. Furthermore, even though both sprinters and hurdlers are high-level athletes, differences in their performance level could be a reason for the different force dominant profile orientation in female sprinters compared to hurdlers and may be a derivative of a relatively small sample size. It should be noted, that the female athletes which involved in the current study were in the top national-level, and participated in the finals of the national championships in athletics competitions. Beyond that, the inverse dynamic model used in our study (Samozino et al., 2008, 2016; Morin et al., 2019) has limitations such as estimating the horizontal aerodynamic drag force from only stature, body mass and a fixed drag coefficient (Arsac and Locatelli, 2002), as well as having the assumption of a quasi-null center of mass vertical acceleration over the sprint-acceleration phase. The latter assumption is more pronounced when using starting blocks and less when starting from a three-point crouching position. Moreover, to ensure valid mechanical output computations based on velocity-time data, as obtained by a high-speed camera, it is crucial to correctly determine the frame corresponding to the start of the sprint which corresponds to the beginning of the force production. We consider the frame at which the athletes thumb left the ground from a three-point starting position as frame 0, which represent the moment of the force production. The same procedure was used in other studies as well (Romero-Franco et al., 2017; Morin and Samozino, 2018). However, we believe that the variables of the F-V and

P-V mechanical profile were not affected by the methods used, since they were in agreement with other studies evaluating the same parameters.

CONCLUSION

The main findings of the present study were that the high-level female sprinters are able to apply higher horizontally-oriented forces onto the ground during acceleration phase than the high-level female hurdlers. The practical applications of the present study support that the F-V-P profile is useful method for researchers and coaches in order to ensure a more specific, accurate and comprehensive characterization of high-level athletes' physical qualities in order to design effective training programs toward to performance maximization.

DATA AVAILABILITY

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethical Commitee of National and Kapodistrian University of Athens. The ethics committee waived the requirement of written informed consent for participation.

AUTHOR CONTRIBUTIONS

ISt and GP contributed to the conception and design of the study. All authors, ISt, ISm, AT, TE and GP participated in data base collection. ISt organized the database and performed the statistical analysis. ISt and ISm wrote the first draft of the manuscript. GP supervised the study. All authors contributed to manuscript revision, read and approved the submitted version.

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World-Class Male Sprinters and High Hurdlers Have Similar Start and Initial Acceleration Techniques

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The effect of the inclusion of a high hurdle 13.72 m after the start line on elite sprint start and initial acceleration technique has yet to be investigated or understood. This highly novel study addresses that lack of information in an exceptional manner, through detailed biomechanical analysis of the world's best sprint and hurdle athletes, with data collected *in situ* at the 2018 IAAF World Indoor Championships, held in Birmingham, UK. High speed videos (150 Hz) were compared for eight sprinters and seven hurdlers for the start and initial acceleration phase of the finals of the men's 60 m and 60 m hurdles. Temporal and kinematic data were supplemented by vector coding analysis to investigate mechanisms by which these world-class athletes translate their centres of mass (CM) up to the fourth touchdown post-block exit. The sprinters and hurdlers coordinated their lower limb and trunk movement in a similar manner throughout the start and initial acceleration phases, which contributes new conceptual understanding of the mechanisms that underpin start and initial acceleration performance. Differences between groups were initiated from block set-up, with the hurdlers utilising a larger block spacing, but with the front block nearer to the start line than sprinters. Even after accounting for stature, the biggest differences in the raising of the CM occurred during the block phase, with hurdlers greater than sprinters (difference in vertical CM displacement scaled to stature = −0.037, very large effect size). Subsequent flight phases showed the biggest differences in the translation of the CM, in part due to longer flight times in the hurdlers, whilst the techniques of the two groups generally converged during the ground contact phases of initial acceleration. In highlighting that similar techniques are used by world-class sprinters and hurdlers, despite differing task constraints, this study has provided invaluable insights for scientists, coaches, and athletes, that will inform further developments in understanding and practice across both sprints and hurdles.

Keywords: acceleration, biomechanics, coordination, hurdles, kinematics, sprint start, track and field, world championships

INTRODUCTION

Although it is well-established that effective maximal sprint acceleration is dependent on primarily horizontal external kinetics (Morin et al., 2011; Rabita et al., 2015) and matching segmental kinematics (Kugler and Janshen, 2010; Nagahara et al., 2014; von Lieres und Wilkau et al., 2018), research has not examined what effect the inclusion of a high hurdle has on acceleration performance and centre of mass (CM) projection. To the authors' knowledge the only published works investigating the initial acceleration phase in sprint hurdlers have been confined to a simple spatio-temporal analysis (Rash et al., 1990) and a single athlete case study covering kinematics, external kinetics, and electromyography (Coh et al., 2007) in female athletes, for whom the hurdles are 0.838 m high. For male high hurdlers, the placement of a 1.067 m high hurdle 13.72 m from the start line introduces an additional task constraint. This is yet to be investigated in terms of its effect on performance in the start and initial acceleration phase, which are critical to optimal overall performance. The initial acceleration phase has previously been defined as lasting four to six steps after block exit (Nagahara et al., 2014; von Lieres und Wilkau et al., 2018).

A key characteristic of a hurdler's approach to the first hurdle is the number of steps taken, which in recent years has shifted to a seven-step pattern among the world's elite. However, the coaching literature has suggested both seven (Freeman, 2015) and eight step approaches (Mann and Murphy, 2018) as closer to initial acceleration mechanics in sprinters. The absence of an examination of initial acceleration mechanics in high hurdles and a detailed comparison of sprint and hurdle start and initial acceleration has important implications for both coach and athlete development as well as the understanding of optimal performance.

The word "elite" is overused in sports science literature, and the number of published studies on the biomechanics of the world's best able-bodied sprinters is small. Out-of-competition data have been presented from the block start (Bezodis et al., 2015; Willwacher et al., 2016), initial acceleration phase (Wild et al., 2018), composite 40 m maximal acceleration (Rabita et al., 2015), maximum velocity phase (Bezodis et al., 2008, 2018), and a full 100 m sprint (Morin et al., 2012) of groups of athletes that generally contained one sub-10 s sprinter. There are also examples of analyses of elite 100 m races based primarily on distance-time data, either taken from broadcast television footage or data from previous IAAF biomechanics projects (e.g., Salo et al., 2011; Taylor and Beneke, 2012; Slawinski et al., 2017). However, to the authors' knowledge, more detailed kinematic analyses of elite athletes in competition are confined to the block and initial acceleration phase from a Diamond League 100 m final (Ciacci et al., 2017) and the home straight of the 1984 Olympic 200 m final (Mann and Herman, 1985b). Lately, the IAAF has published detailed biomechanical reports from both outdoor and indoor World Championships (Bissas et al., 2018; Pollitt et al., 2018; Walker et al., 2019a,b). However, the lack of peer-reviewed analysis of "world-class sprinters (e.g., international finalists)" has very recently been highlighted in a comprehensive review of the biomechanics of the sprint start as a major gap in the research literature (Bezodis et al., 2019b).

The inherent nature of biomechanical data collection with elite athletes in competition necessitates an approach that minimises interference with the athletes. This usually means that studies conducted in these settings have to focus on kinematic analyses (e.g., Mann and Herman, 1985a,b; Ciacci et al., 2017). Studies of sub-elite athletes have demonstrated that segmental orientations closely reflect the external force characteristics that are important for effective maximal sprint acceleration (Kugler and Janshen, 2010; Nagahara et al., 2014; von Lieres und Wilkau et al., 2018). Therefore, kinematic analyses can play an important role in improving the understanding of the mechanisms that underpin effective sprint start and acceleration performance. The role of the trunk segment during the block phase (Slawinski et al., 2012), and of the shank and trunk segments during the initial acceleration phase (von Lieres und Wilkau et al., 2018) have been shown to be important for efficient performance. At a joint kinetic level in the initial acceleration phase, the ankle plantarflexors and hip extensors are important energy generators (Charalambous et al., 2012; Bezodis et al., 2014; Brazil et al., 2017), whilst the magnitude of knee extensor energy generation is thought to relate to sprint performance (Debaere et al., 2013; Bezodis et al., 2014; Brazil et al., 2018).

Studies of the block and initial acceleration phases of sprinters have shown mechanisms by which they project their CM to address the task. Debaere et al. (2013) reported horizontal and vertical block exit velocities of 3.10 and 0.84 m/s, respectively. Whereas the horizontal velocity increased in a relatively consistent linear manner throughout the block phase, the vertical velocity increased rapidly through the initial double-leg push phase, peaking at 0.74 m/s, and then only showing a small further increase up to block exit. This suggests that there is an equal focus on both forward and upward projection of the CM during the double-leg push phase, but that this switches to a primary focus on the forward projection of the CM during the single-leg push phase. Characteristics of external force data gathered during the block phase support this suggestion (Willwacher et al., 2016; Bezodis et al., 2019a), and it has previously been shown that rear-leg force production in the blocks is a key discriminant of sprint performance in athletes ranging from national level to world-class (Fortier et al., 2005; Willwacher et al., 2016; Brazil et al., 2018).

The assessment of coordination offers an advancement beyond single-joint kinematic analysis to understand sports technique, offering insight into the interaction between components of the biological system that are functionally linked to satisfy the demands of a given task (Bernstein, 1967; Turvey, 1990). The theoretical model of constraints on action (Newell, 1986) describes how individuals adopt movement coordination patterns via self-organisation within the context of organismic, environmental and task related constraints imposed on the biological system. These coordination patterns are commonly assessed through investigating the relative motion between joints or segments of the same limb, providing a measure of intra-limb coordination (Sparrow et al., 1987) that can improve understanding of how gross movement is organised, and for gait, therefore, how the translation of the CM is controlled. Intra-limb coordination analyses have been applied to constant velocity locomotive task such as walking (Chang et al., 2008), running (Hamill et al., 1999; Floría et al., 2019), and maximal velocity sprinting (Gittoes and Wilson, 2010). Vector coding methods (Sparrow et al., 1987; Chang et al., 2008; Needham et al., 2014) output a coupling angle, which can be easily related back to angular motion, providing an intuitive applied method for assessing movement coordination. To the authors' knowledge, coordination analyses have not yet been applied to the block and initial acceleration phases of a maximal sprint in an elite population. Given the additional task constraint of the high hurdle, inter-segment coordination analyses will afford greater insight into technique differences between elite sprint and hurdle athletes.

The purpose of this study was therefore to address the gaps in the research literature in an exceptional way, based on detailed biomechanical data collected from the finals of the 2018 IAAF World Indoor Championships. This is the first time in the biomechanics research literature that such data have been captured live, enabling a novel approach to examining an important aspect of sprint acceleration performance. The first aim of the study was to quantify and explain the start and initial acceleration technique of the world's best male sprinters and hurdlers *in situ* in an elite competition environment. Secondly, based on a comparison of the sprinters and hurdlers, the aim was to elucidate the mechanisms by which the athletes translate their CM during the start and initial acceleration phases, given the different task constraints placed on the athletes by the two events. Findings from this study will contribute new conceptual understanding of the mechanisms that underpin start and initial acceleration performance, for scientists, coaches and athletes.

MATERIALS AND METHODS

Participants

Data were collected as part of the Birmingham 2018 IAAF World Indoor Championships Biomechanics Research Project. The use of the data for this study was approved by the IAAF, who own and control the data, and locally through institutional research ethics procedures. The study was approved by the Leeds Beckett University Ethics sub-committee (School local approval by Research Ethics Coordinator). The patients/participants provided their written informed consent to participate in this study. The fifteen finalists of the men's 60 m and 60 m hurdles races (eight sprinters and seven hurdlers, because of a false start) were analysed in their respective races, on the evenings of 3rd and 4th March 2018 at Arena Birmingham, UK. All hurdlers took a seven-step approach to the first hurdle.

Data Collection

Four Sony PXW-FS7 cameras operating at 150 Hz (shutter speed: 1/1250 s; ISO: 2000–4000; FHD: 1920 × 1080 pixels) were used to capture motion of athletes during block and initial acceleration phases (see **Figure 1**). A calibration procedure was conducted before and after each race. A rigid cuboid calibration frame measuring 3.044 × 3.044 × 3.044 m and comprising 24 control points was used. It was sequentially positioned multiple times over discrete predefined areas along and across the track to ensure an accurate definition of a volume covering the starting blocks and initial acceleration phase of the race, from 1 m behind the start line to 5 m beyond the start line. This approach produced a large number of non-coplanar control points per individual calibrated volume and facilitated the construction of a local coordinate system in each neighbouring pair of lanes, that was then combined into a global coordinate system, originating 1 m behind the left edge of lane 1.

Data Processing

The video files were imported into SIMI Motion (SIMI Motion version 9.2.2, Simi Reality Motion Systems GmbH, Germany) and were manually digitised by a single experienced operator to obtain kinematic data. An event synchronisation technique (synchronisation of four critical instants) was applied through SIMI Motion to synchronise the two-dimensional coordinates from each camera involved in the recording. The digitising was carried out in two parts: a whole body analysis of specific discrete key events, and a continuous analysis of the trunk and rear leg throughout the start and initial acceleration phase. Firstly, a 17 point whole body model was digitised at the following key events; first visible movement from the set position (FM), rear foot block exit (RFBE), front foot block exit (FFBE), and touchdown and take-off events up to the touchdown of ground contact four ($GC1_{TD}$, $GC1_{TO}$ etc... see **Table 1**). From block exit onwards, these events were defined as the last frame where the foot was visibly on the block or track, and the subsequent first frame where the foot was visibly on the track, respectively. The 17 digitised points were the centre of the head, and bilaterally shoulder, elbow, wrist, metacarpo-phalangeal, hip, knee, ankle, and metatarso-phalangeal (MTP) joint centres in accordance with de Leva (1996).

Secondly, the shoulder, hip, knee, ankle, and MTP joints on the side of the rear leg in the blocks were digitised continuously in every frame from the onset of movement in the blocks (FM) to the third take-off after block exit ($GC3_{TO}$). Each video file was digitised frame by frame and upon completion, adjustments were made as necessary using the points over frame method (Bahamonde and Stevens, 2006). The Direct Linear Transformation algorithm (Abdel-Aziz and Karara, 1971) was used to reconstruct the three-dimensional coordinates from individual camera's x and y image coordinates. For all subsequent analysis, three-dimensional coordinates were projected onto a two-dimensional sagittal plane using only antero-posterior and vertical coordinates. Reliability of the digitising process was estimated by repeating the process for specific variables for eight randomly selected athletes with an intervening period of 48 h. The results showed minimal total errors (CM vertical coordinate in the set position: RMSD = 0.0056 m, ICC = 0.999; knee angle at third touchdown: RMSD = 1.0°, ICC = 0.994) and therefore confirmed the high reliability of the digitising process.

All further data processing was done in Matlab (v2019a, Natick, MA). de Leva (1996) body segment parameter model was used to obtain data for the whole body CM and for key body segments of interest. A recursive second-order, low-pass

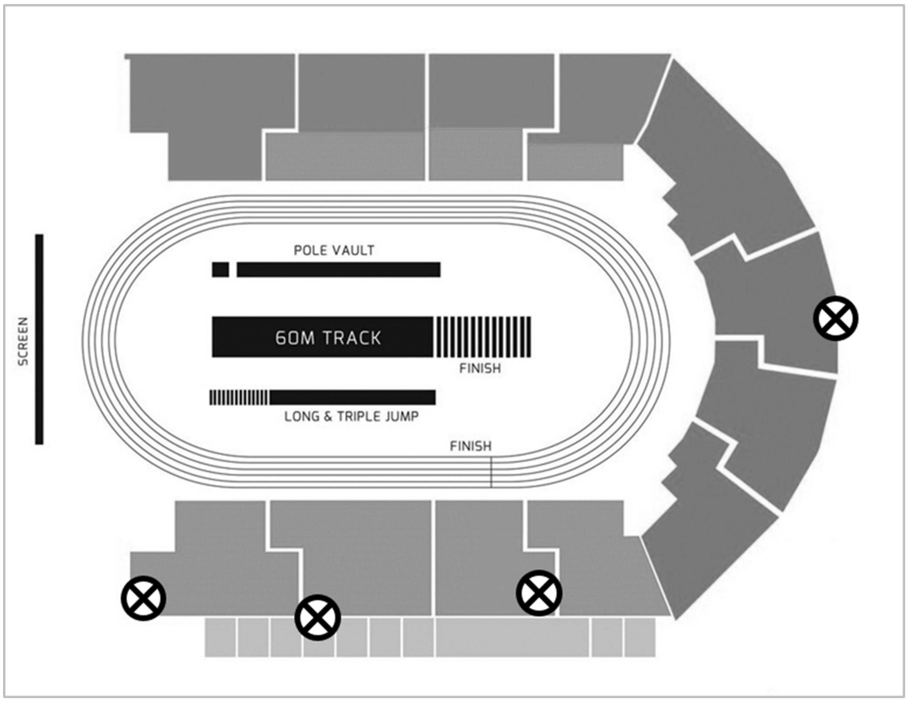

FIGURE 1 | Camera positions for data capture. The four cameras are each marked with an ⊗.

Butterworth digital filter (zero phase-lag) was employed to filter the raw coordinate data for the five joint centres digitised continuously throughout the movement. The cut-off frequencies were calculated (mean 13.3 Hz, range 10.0–15.5 Hz) using residual analysis (Winter, 2009).

For the whole-body analysis at key events, all linear displacement variables (horizontally and vertically for CM and joint centres) were scaled according to the stature of the athletes measured from the digitised data, to account for any differences in height between the two groups. Based on the approach of Ciacci et al. (2017), the sum of the length of shank, thigh and trunk segments was calculated for each athlete for all frames. All linear displacements were divided by this individual scaling factor (mean: 1.359 m for sprinters and 1.456 m for hurdlers), and are therefore presented as dimensionless values. Block spacings were calculated based on the coordinates of the two MTP joint centres in the set position, and were not scaled to stature. Segment angles were defined in an anticlockwise direction relative to the global forward horizontal, and joint angles were defined with extension as positive (see **Figure 2**).

For the continuous data analysis of the shoulder, hip, knee, ankle and MTP joints on the side of the rear leg in the blocks, all relevant data (joint centre coordinates and segment angles) were time normalised based on key events relevant to the rear foot in the blocks. Those six events were FM, RFBE, $GC1_{TD}$, $GC1_{TO}$, $GC3_{TD}$, and $GC3_{TO}$. Between each successive event the data were time-normalised to 101 data points using a cubic spline. This gave a total of 501 data points from FM to $GC3_{TO}$. The mean value of the time of FFBE for each group was calculated as a percentage between the RFBE and $GC1_{TD}$ events.

TABLE 1 | Abbreviations used in the study.

Abbreviation	Meaning
CM	Centre of mass
FM	First movement
RFBE	Rear foot block exit
FFBE	Front foot block exit
GC1, GC2, GC3	Ground contact one, two and three
$GC1_{TD}$, etc…	Ground contact one touchdown, etc…
$GC1_{TO}$, etc…	Ground contact one take-off, etc…
MTP	Metatarso-phalangeal
SD	Standard deviation
CA	Coupling angle
CA_{DIF}	Coupling angle difference

All between group comparisons were made using group means and standard deviations (SD), with unpaired samples 95% confidence intervals calculated, based on the differences between the two groups (Altman and Gardner, 2000). All differences were calculated as sprinters minus hurdlers. Group responses were considered different where the 95% confidence intervals did not cross zero (Altman and Gardner, 2000), for both discrete and continuous data. Analysis of discrete data was supplemented with effect size (Cohen's *d*) calculations, with mean and pooled SD calculated according to Altman and Gardner (2000). The effect size magnitude was classified according to the scale proposed by Hopkins et al. (2009). Positive effect sizes represented comparisons where sprinters had a larger value than hurdlers,

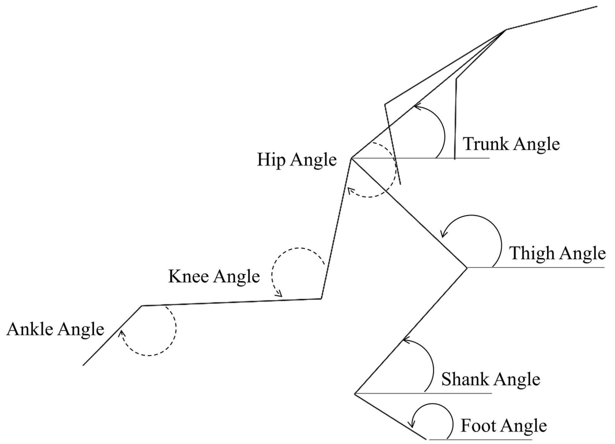

FIGURE 2 | Segment and joint angle definitions used in the study. Segment angles are represented on the ground leg (right, solid line), and joint angles are represented on the swing (left) leg.

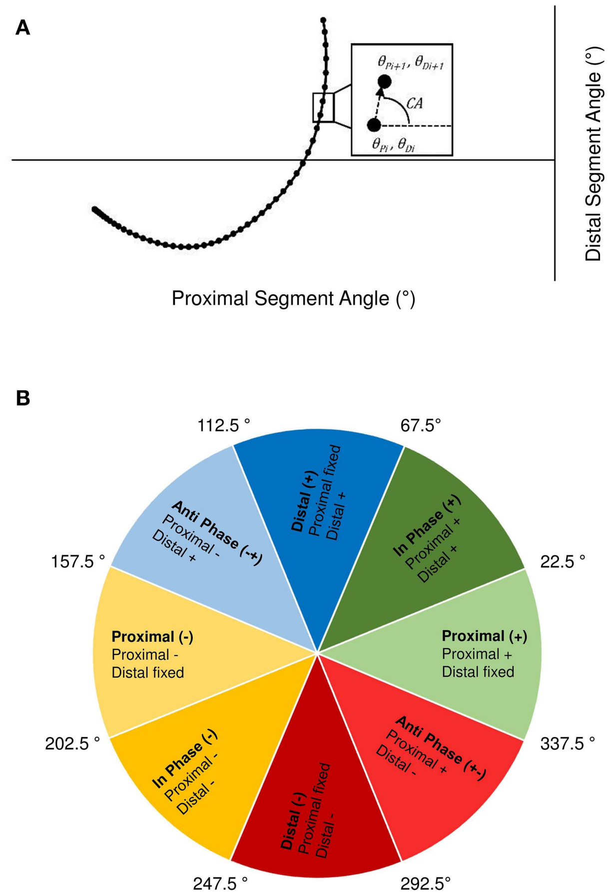

FIGURE 3 | Definition of the coupling angle (CA) from segmental angle-angle plots **(A)** and classification of coordination patterns into distinct "bins" based on the relative motion of the proximal and distal segment **(B)**. Anticlockwise and clockwise segment rotation are defined as positive (+) and negative (–), respectively.

and negative effect sizes represented comparisons where hurdlers had a larger value than sprinters. Data are presented in the results as (difference in means, 95% confidence interval, effect size classification), according to Altman and Gardner (2000).

Intra-Limb Coordination Analysis

Vector coding techniques (Chang et al., 2008; Needham et al., 2014) were applied to individual and ensemble group mean angle-angle plots for the trunk-thigh, trunk-shank and thigh-shank couples, to obtain the coupling angle (CA) at each instance of the normalised time cycle between FM and $GC3_{TO}$. Specifically, CA was calculated as the orientation of the vector between two adjacent points on the angle-angle plot, relative to the right horizontal and expressed between 0 and 360° (**Figure 3A**). CA data were then "binned" into one of eight distinct coordination patterns (Chang et al., 2008) based on each segment's relative motion (**Figure 3B**), with each coordination pattern assigned a specific colour. The colour assignment could then be used to profile coordination across the normalised time cycle to aid visual identification of coordination differences within and between each group. To quantify overall differences in coordination between the sprint and hurdle groups, a coupling angle difference (CA_{DIF}) was calculated, by computing a "difference score" in coordination pattern (bin), ranging from 0 (same bin) to 4 (opposite bin) at each instance across the normalised time cycle (**Figure 3B**). The sum of each difference score was then expressed as a percentage of the maximum possible value, with a lower CA_{DIF} representing closer similarity in coordination patterns.

RESULTS

Discrete Analysis at Key Events

Visual inspection of whole body positions adopted by the two groups at key events (**Figure 4**) showed differences in block spacings and thigh angles at first movement, but otherwise similar patterns were observed at block exit events. At subsequent touchdown and take-off events sprinters' trunk and shank segments were generally more forward orientated than hurdlers'. Additional temporal analysis (**Table 2**) showed that although reaction time was identical, hurdlers spent longer in both double- and single-leg push (double-leg difference −0.023 s, −0.043 to −0.003, large effect; single-leg difference −0.031 s, −0.050 to −0.012, large effect) and the total block phase (difference −0.054 s, −0.080 to −0.028, very large effect). With the exception of contact time for ground contacts two and four, all contact and flight times were longer in the hurdlers (medium to very large effects). Overall, the total time to the fourth take-off was greater in the hurdlers than the sprinters (difference −0.228 s, −0.268 to −0.188, extremely large effect). The hurdlers' blocks were set up with both feet nearer to the start line (front foot difference 0.24 m, 0.16 to 0.33, very large effect; rear foot difference 0.13 m, 0.03 to 0.24, large effect), and a greater spacing between the two blocks (difference −0.10 m, −0.17 to −0.04, large effect).

The clearest differences in translation of the CM occurred during the block phase, particularly after rear foot block exit,

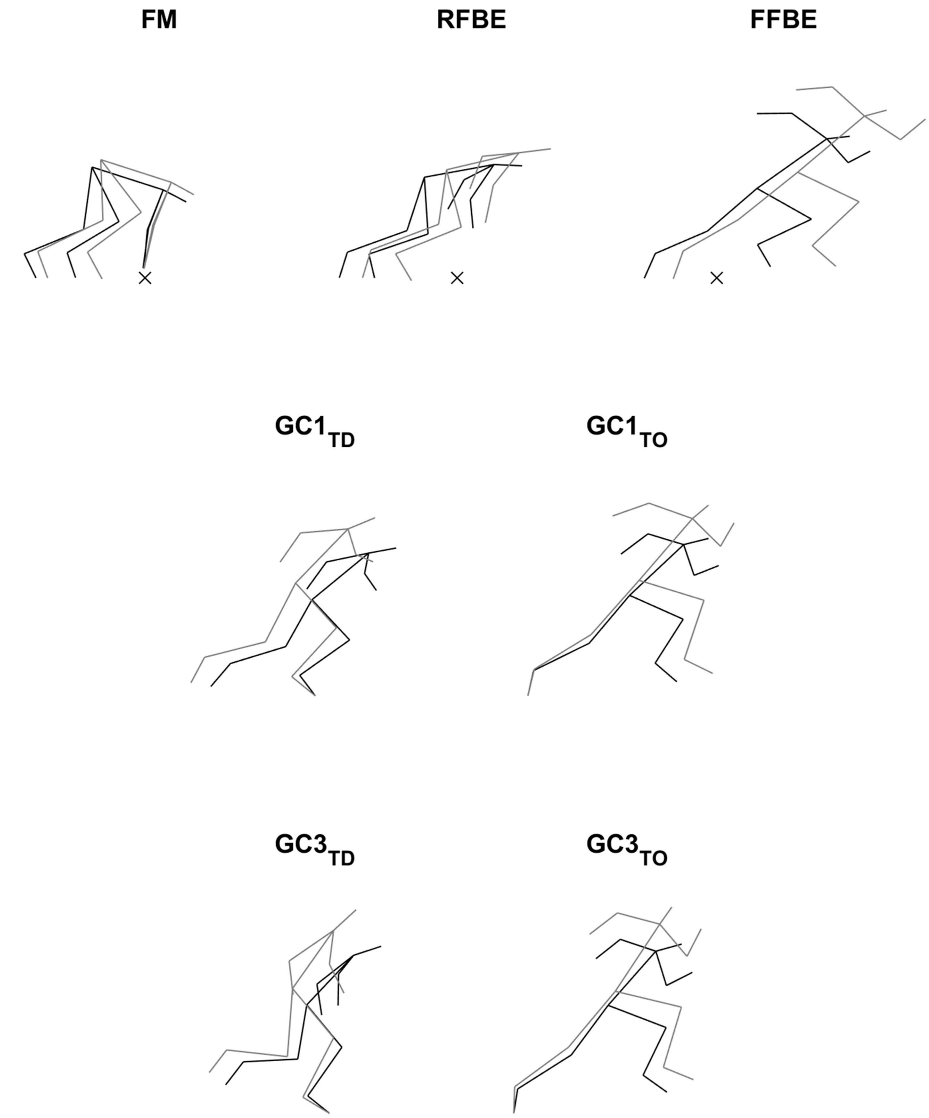

FIGURE 4 | Stick figures showing absolute mean segmental orientations of sprinters (black) and hurdlers (grey) at key events related to the rear leg in the blocks. Block phase events are aligned according to the mean locations of the metacarpal-phalangeal joint centres, with the start line marked (×). Touchdown and take-off events are aligned to the mean locations of the MTP joint of the ground contact leg.

and during the flight phases succeeding each post-block foot contact. Hurdlers displaced their CM vertically and horizontally more than sprinters between RFBE and FFBE (vertical difference −0.037, −0.057 to −0.018, very large effect; horizontal difference −0.075, −0.111 to −0.038, very large effect, **Figures 5A,B**). Differences in CM vertical displacement changes between RFBE and FFBE were mirrored in changes at the shoulder (vertical difference −0.039, −0.068 to −0.011, large effect), hip (vertical difference −0.051, −0.080 to −0.022, large effect) and knee (vertical difference −0.049, −0.082 to −0.016, large effect) during the same phase, which were all greater in hurdlers than sprinters (**Figures 6A–C**).

Whilst there was a clear overlap in confidence intervals for change of CM vertical displacement between FM and RFBE (difference −0.011, −0.026 to 0.004, moderate effect, **Figure 5A**), the range of responses was clearly greater in hurdlers than sprinters, indicating more variability within the hurdler group (SD hurdlers 0.019, SD sprinters 0.005). This was reflected in more variability in the hurdlers in the vertical displacement of both hip (SD hurdlers 0.043, SD sprinters 0.031) and knee joint centres (SD hurdlers 0.035, SD sprinters 0.014), but less variability in the raising of the shoulder (SD hurdlers 0.014, SD sprinters 0.032). At each of those joints there was a clear overlap in the confidence intervals for the magnitude of the change in CM vertical displacement (small effect, shoulder and knee; no difference, hip; **Figures 6A–C**).

During initial acceleration hurdlers produced greater horizontal CM displacement than sprinters in each of the second

TABLE 2 | Durations of key phases from the starting gun to the end of the fourth foot contact, and block spacing distances, for sprinters and hurdlers (Mean ± SD).

Variable	Sprinters	Hurdlers	Difference	95% Confidence interval	Effect size (*d*)
Reaction time [s]	0.155 ± 0.010	0.155 ± 0.018	<0.001	−0.016 to 0.016	0.01ND
Double-leg push time [s]	0.194 ± 0.018	0.217 ± 0.018	−0.023	−0.043 to −0.003*	−1.29^{L}
Single-leg push time [s]	0.148 ± 0.018	0.179 ± 0.016	−0.031	−0.050 to −0.012*	−1.81^{L}
Total block time [s]	0.497 ± 0.027	0.551 ± 0.018	−0.054	−0.080 to −0.028*	−2.32^{VL}
Flight time 1 [s]	0.044 ± 0.012	0.077 ± 0.016	−0.033	−0.048 to −0.018*	−2.39^{VL}
Contact time 1 [s]	0.175 ± 0.014	0.210 ± 0.034	−0.035	−0.064 to −0.007*	−1.40^{L}
Flight time 2 [s]	0.058 ± 0.012	0.083 ± 0.013	−0.025	−0.040 to −0.011*	−1.99^{L}
Contact time 2 [s]	0.171 ± 0.014	0.165 ± 0.016	0.006	−0.011 to 0.023	0.41^{S}
Flight time 3 [s]	0.063 ± 0.012	0.099 ± 0.012	−0.037	−0.050 to −0.023*	−2.96^{VL}
Contact time 3 [s]	0.138 ± 0.011	0.154 ± 0.018	−0.017	−0.033 to −0.001*	−1.16^{M}
Flight time 4 [s]	0.072 ± 0.010	0.099 ± 0.010	−0.027	−0.038 to −0.016*	−2.78^{VL}
Contact time 4 [s]	0.136 ± 0.016	0.142 ± 0.008	−0.006	−0.020 to 0.008	−0.48^{S}
Total time to end of fourth contact [s]	1.352 ± 0.040	1.580 ± 0.029	−0.228	−0.268 to −0.188*	−6.40^{EL}
Front foot toe distance from start line in blocks [m]	0.56 ± 0.05	0.33 ± 0.08	0.24	0.16 to 0.33*	3.36^{VL}
Back foot toe distance from start line in blocks [m]	0.84 ± 0.05	0.71 ± 0.12	0.13	0.03 to 0.24*	1.40^{L}
Block spacing [m]	0.28 ± 0.03	0.38 ± 0.08	−0.10	−0.17 to −0.04*	−1.70^{L}

*Differences are calculated as sprinters minus hurdlers, so negative values represent values for hurdlers being greater than sprinters. *Represents where the confidence interval for the between group comparison does not cross zero (Altman and Gardner, 2000). Effect size scale (Hopkins et al., 2009): No Difference (ND) = < 0.20; Small (S) = ≥ 0.20 to < 0.60; Moderate (M) = ≥ 0.60 < 1.20; Large (L) = ≥ 1.20 to < 2.00; Very Large (VL) = ≥ 2.00 to < 4.00; Extremely Large (EL) = ≥ 4.00.*

to fourth flight phases ($GC1_{TO}$-$GC2_{TD}$ difference −0.110, −0.169 to −0.052, very large effect; $GC2_{TO}$-$GC3_{TD}$ difference −0.097, −0.157 to −0.037, large effect; $GC3_{TO}$-$GC4_{TD}$ difference −0.181, −0.247 to −0.114, very large effect; **Figure 5B**). These group-level differences in change in CM horizontal displacement were reflected by the shoulder, hip, knee, and ankle in each of the second, third and fourth flight phases (large to very large effects, **Figure 7**).

Continuous and Angular Analysis

During the first swing phase (at 160% normalised time from FM to $GC3_{TO}$ i.e., at 60% time from RFBE to $GC1_{TD}$), the hurdlers had raised their shoulders to a greater extent, when accounting for stature, and maintained this through the remainder of the initial acceleration phase (**Figure 8B**). There were no clear differences in joint and segment angles of the rear leg in the set position, but moderate effect sizes for a more flexed hip and vertical thigh in the hurdlers (**Figure 9**, **Table 3**). The front leg hip angle was more flexed in the hurdlers in the set position (difference 10°, 2 to 18, large effect), with no clear differences but a moderate effect size for hurdlers' thigh being more horizontal and shank being more vertical (**Figure 9**, **Table 3**).

After FM, hurdlers briefly had a more vertically orientated thigh segment than sprinters during the double-leg push phase (from 47 to 71% time) and around the transition from double- to single-leg push (93–124% time, **Figure 9D**). During the initial acceleration phase, hurdlers had more vertically orientated trunk and shank segments, as well as a more horizontally orientated foot segment late in the first swing and early into the first ground contact phase (trunk, 161–230% and 239–279%, **Figure 9B**; shank 156–268%, **Figure 9F**; foot 153–280%, **Figure 9H**). These differences at the trunk, shank, and foot occurred again late in the second swing phase and into the third ground contact (trunk, 286–500%, **Figure 9B**; shank 348–440%, **Figure 9F**; foot 349–479%, **Figure 9H**), and continued thereafter at the trunk, with a more upright posture maintained throughout the initial acceleration phase. The thigh segment was briefly more upright in the hurdlers late in the second swing phase (from 361 to 379% time, **Figure 9D**). The only clear difference in the ranges of motion of joints or segments between each of the key events investigated, was at the foot during the first ground contact (difference 15°, 1 to 30, moderate effect, **Table 3**). There were, however, also moderate effect sizes for range of motion of the trunk segment between FM and both RFBE and $GC1_{TD}$, with hurdlers showing greater values (FM-RFBE difference −6°, −15 to 4, moderate effect; FM-$GC1_{TD}$ difference −8°, −17 to 1, moderate effect).

Intra-Limb Segmental Coordination

Trunk-Thigh

Coordination of the trunk-thigh segments was similar between groups, with CA_{DIF} magnitudes of 7% during the double-leg push phase and 1–3% after RFBE (**Figure 10**). The greater difference during the double-leg push was mainly attributed to the onset of movement. From FM, sprinters exhibited an earlier transition and longer duration of distal (–) coordination (dark red), whereas hurdlers spent a greater duration of this initial movement in coordination patterns dominated by anticlockwise trunk rotation (anti phase +−, light red; in-phase +, dark green, **Figure 10**). During GC_1 and GC_3 both groups exhibited a dominance of distal (–) coordination as the thigh rotated clockwise and trunk angle remained relatively fixed (**Figures 10**, **11**).

Trunk-Shank

The greatest inter-group and inter-individual differences in trunk-shank coordination were again attributed to the onset

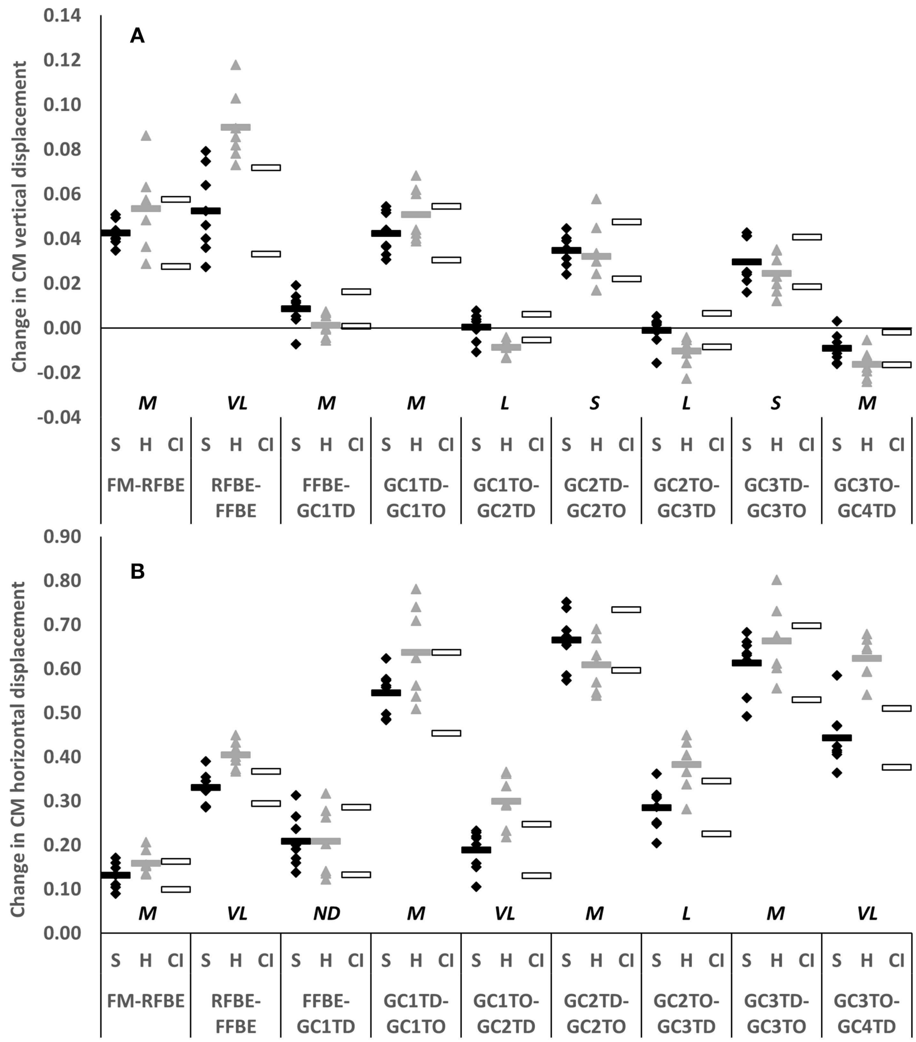

FIGURE 5 | Change in vertical **(A)** and horizontal displacement **(B)** of whole body CM of sprinters (black diamonds) and hurdlers (grey triangles) between successive key events, scaled to stature. Group means are represented by shaded rectangles, and 95% confidence intervals with white rectangles. Values for hurdlers are different from sprinters where the hurdlers mean falls outside the 95% confidence intervals [i.e., where the confidence interval for the between group comparison does not cross zero (Altman and Gardner, 2000)]. Effect size classifications are represented above x-axis labels (Hopkins et al., 2009): No Difference (*ND*) = < 0.20; Small (*S*) = ≥ 0.20 to < 0.60; Moderate (*M*) = ≥ 0.60 < 1.20; Large (*L*) = ≥ 1.20 to < 2.00, Very Large (*VL*) = ≥ 2.00 to < 4.00; Extremely Large (*EL*) = ≥ 4.00.

of movement (**Figures 10**, **11**). Of all phases during initial acceleration CA_{DIF} was higher during the double-leg push phase (10%), first swing (12%) and GC_1 (14%), although coordination patterns between the two groups were often within one bin (**Figure 10**). An earlier onset of anticlockwise shank rotation after RFBE in the hurdle group resulted in an earlier transition away from anti phase (+−) coordination, through to in-phase (+) and eventually distal (+) coordination once the trunk ceased anticlockwise rotation (**Figure 10**). During GC_1, group differences in coordination arose around mid-stance, with sprinters and hurdlers showing proximal (–) and in phase (–) patterns, respectively. Individual analysis (**Figure 11**) again highlighted the overall consistency within and between groups with all athletes adopting the same main patterns of coordination after movement onset. Individual differences manifested themselves through temporal shifts between coordination patterns and the time spent in each, as opposed to any clear differences in the major coordination patterns adopted.

Thigh-Shank

At a group level, the largest CA_{DIF} was apparent during GC_3 (18%) as patterns of proximal (–) and anti phase (–+) dominated for the sprint and hurdle groups, respectively, although absolute differences in the coupling angle were small (**Figure 10**). Once more, both group and individual analyses highlighted the overall consistency in coordination patterns, with temporal differences in the transition between major coordination patterns dictating inter-group and inter-individual differences (**Figures 10**, **11**).

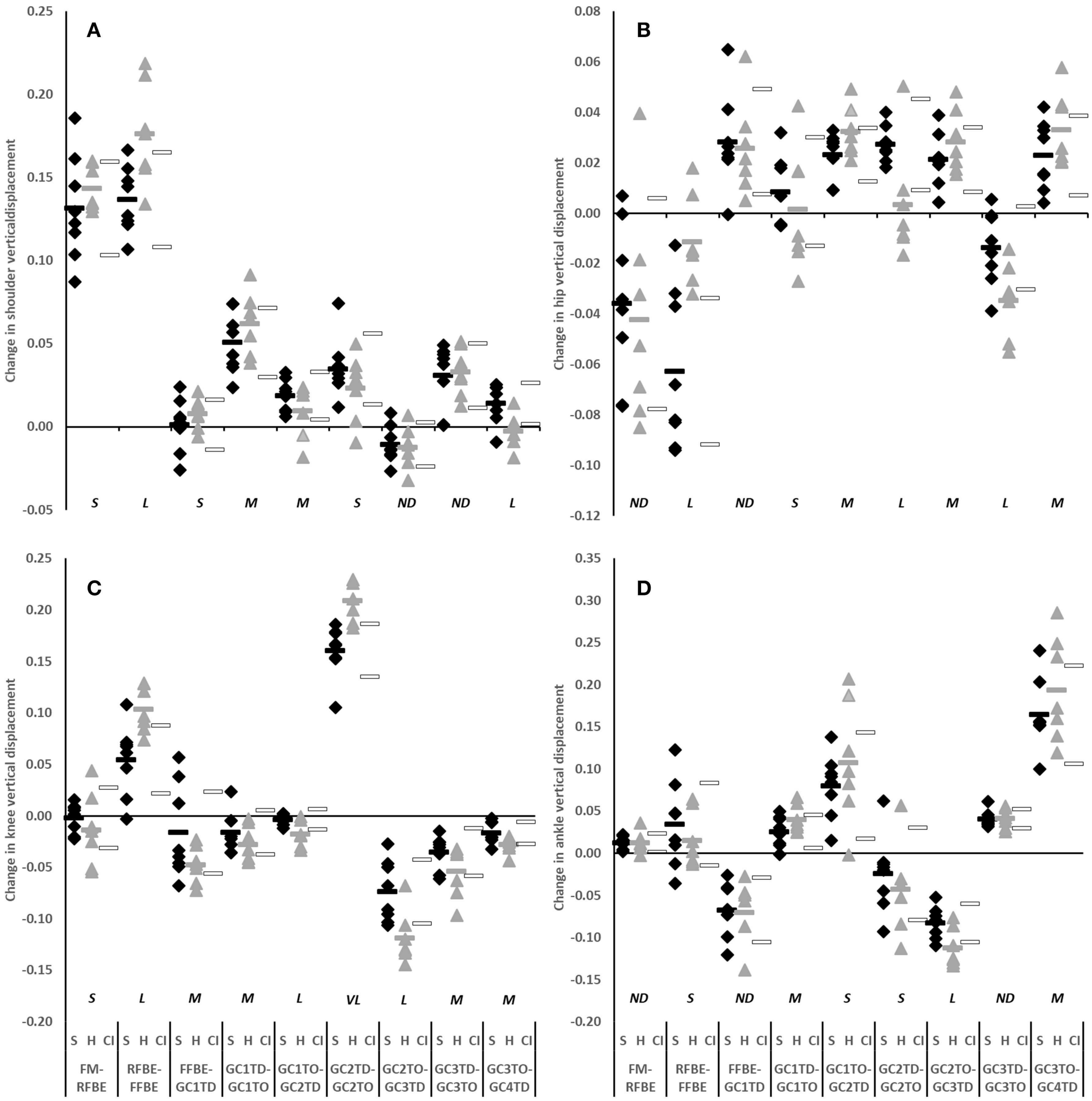

FIGURE 6 | Change in vertical displacement of shoulder **(A)**, hip **(B)**, knee **(C)**, and ankle **(D)** of sprinters (black diamonds), and hurdlers (grey triangles) between successive key events, scaled to stature. Group means are represented by shaded rectangles, and 95% confidence intervals with white rectangles. Values for hurdlers are different from sprinters where the hurdlers mean falls outside the 95% confidence intervals [i.e., where the confidence interval for the between group comparison does not cross zero (Altman and Gardner, 2000)]. Effect size classifications are represented above x-axis labels (Hopkins et al., 2009): No Difference (*ND*) = < 0.20; Small (*S*) = ≥ 0.20 to < 0.60; Moderate (*M*) = ≥ 0.60 < 1.20; Large (*L*) = ≥ 1.20 to < 2.00, Very Large (*VL*) = ≥ 2.00 to < 4.00; Extremely Large (*EL*) = ≥ 4.00.

DISCUSSION

The first aim of this study was to quantify and explain the start and initial acceleration technique of the world's best male sprinters and hurdlers *in situ* in an elite competition environment. This is the first time in the biomechanics research literature that such data have been captured live, in this case from the finals of the 2018 IAAF World Indoor Championships, enabling a novel approach to examining an important aspect of sprint acceleration performance. Secondly, based on a comparison of the sprinters and hurdlers, the aim was to elucidate the mechanisms by which the athletes translate their CM during the start and initial acceleration phases. Despite the different task constraints placed on the athletes by the two events, there were many similarities between the kinematic and inter-segment coordination profiles of the world-class sprinters and hurdlers investigated in the current study.

Overall, the similarity in coordination patterns found in this study (**Figures 10**, **11**) is an important and novel finding that will be particularly useful for scientists, coaches and

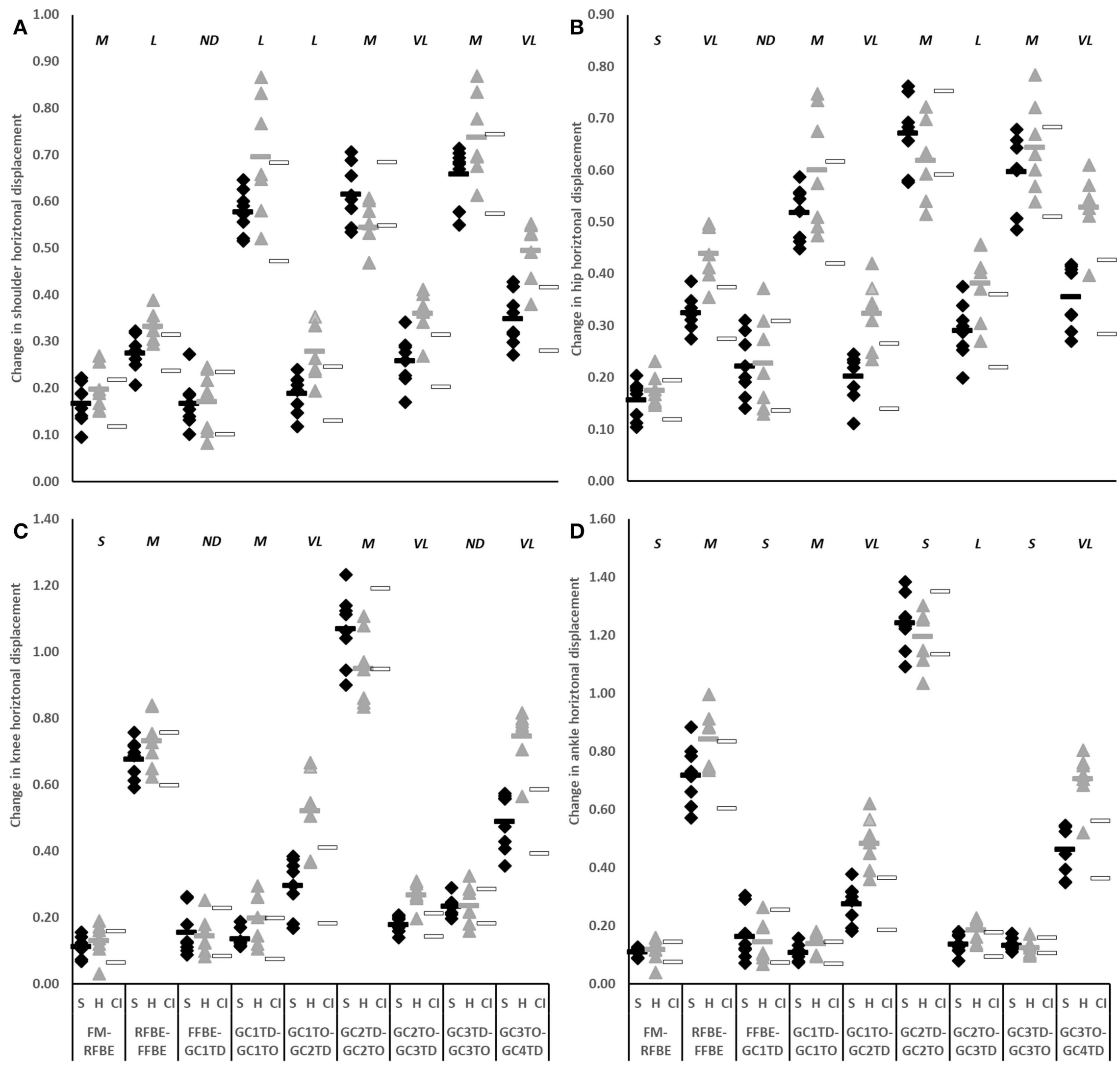

FIGURE 7 | Change in horizontal displacement of shoulder **(A)**, hip **(B)**, knee **(C)**, and ankle **(D)** of sprinters (black diamonds), and hurdlers (grey triangles) between successive key events, scaled to stature. Group means are represented by shaded rectangles, and 95% confidence intervals with white rectangles. Values for hurdlers are different from sprinters where the hurdlers mean falls outside the 95% confidence intervals [i.e., where the confidence interval for the between group comparison does not cross zero (Altman and Gardner, 2000)]. Effect size classifications are represented above x-axis labels (Hopkins et al., 2009): No Difference (*ND*) = < 0.20; Small (*S*) = ≥ 0.20 to < 0.60; Moderate (*M*) = ≥ 0.60 < 1.20; Large (*L*) = ≥ 1.20 to < 2.00, Very Large (*VL*) = ≥ 2.00 to < 4.00; Extremely Large (*EL*) = ≥ 4.00.

athletes. The world-class sprinters and hurdlers studied here organised their lower limb and trunk movement in a similar manner, and this contributes new conceptual understanding of the mechanisms that underpin start and initial acceleration performance. The differences in the raising of the CM are unlikely to be a result of differences in coordination through the start and initial acceleration phase, but result from small differences in the set position and a summation of small to moderate differences in extension range of motion throughout each push-off phase (**Table 2**). Those differences in the set position often come about as a strategic decision by coach and hurdler, to ensure that the athlete has less total distance to cover to reach the first hurdle (Mann and Murphy, 2018).

Following a near-identical reaction time in the sprinters and hurdlers, phase times were longer in hurdlers than sprinters in all phases up to take-off from the fourth contact, with the exception of the contact times when the front leg in the blocks was in contact with the track. These longer phase durations (**Table 2**), in addition to the hurdlers displacing their CM more horizontally during the single-leg push on the blocks and flight phases following the first post-block ground contact (**Figure 5**), might be a consequence of all hurdlers adopting a seven-step approach to the first hurdle. However, with no hurdlers electing

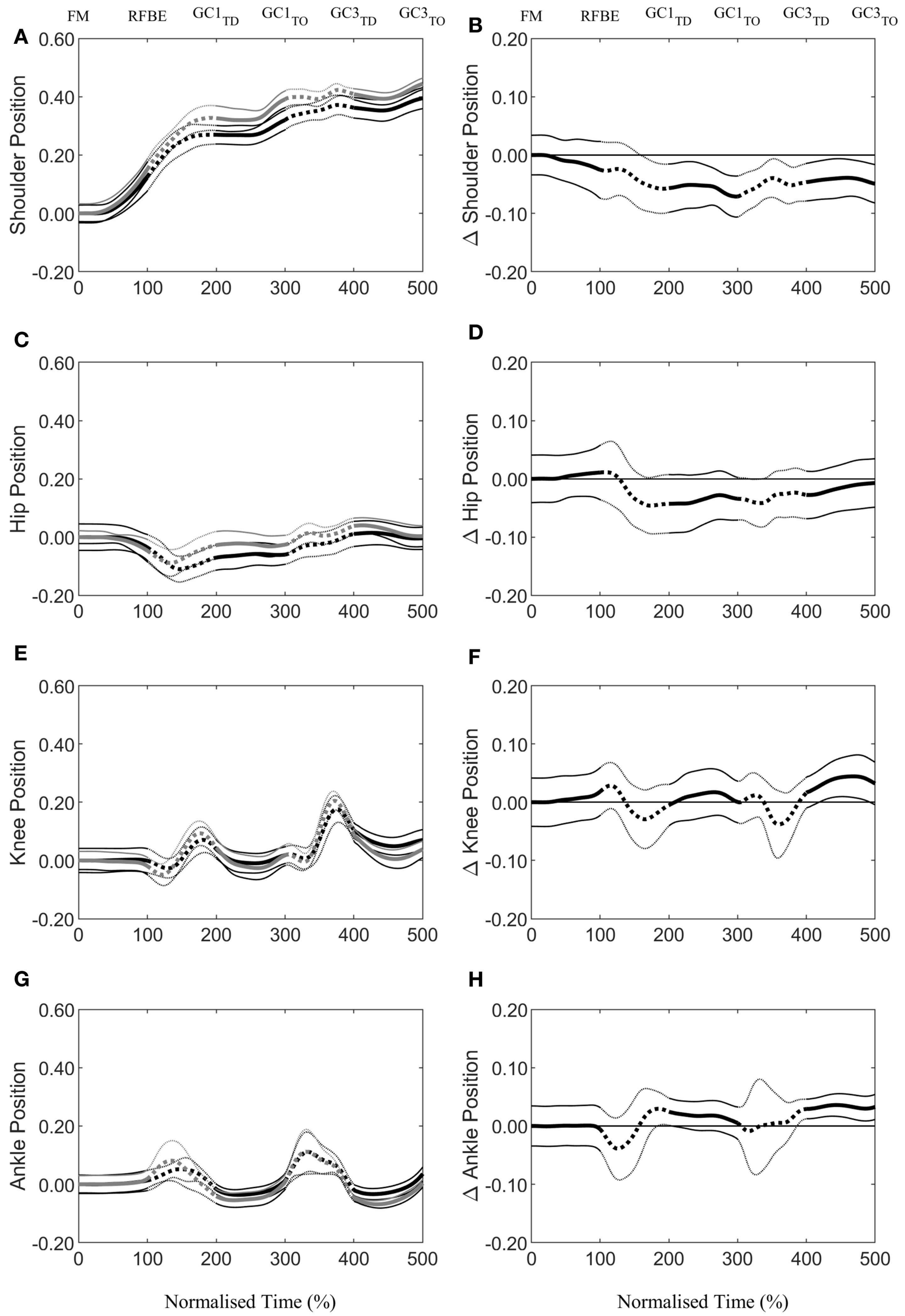

FIGURE 8 | Continuous vertical position relative to the set position (Mean ± SD) of the shoulder **(A)**, hip **(C)**, knee **(E)**, and ankle **(G)**, scaled to individual stature for sprinters (black) and hurdlers (grey), and corresponding differences **(B,D,F,H)** between the sprinters, and hurdlers (thick line), and 95% confidence interval (thin line). Positive differences indicate a greater value for sprinters, and negative differences a greater value for hurdlers. Sections where the confidence interval bands do not cross zero (x-axis) represent clear differences between groups. Solid lines represent the double-leg push phase in the blocks, and first and third ground contacts, whereas dashed lines represent the first and second swing phases of the rear leg, with key events related to the rear leg in the blocks marked above the figure.

to adopt an eight-step approach in this final, a direct comparison of the two strategies is not possible. Nonetheless, the seven-step approach to the first hurdle demands steps in the initial acceleration phase on average to be lengthened, both spatially and temporally (Mann and Murphy, 2018), and that was clearly evident here in comparison to the sprinters. It was interesting to note that the contact times that showed no difference between hurdlers and sprinters were those that were taken with what would be the lead leg during subsequent hurdle clearances. It is beyond the scope of this study to investigate the differing roles of

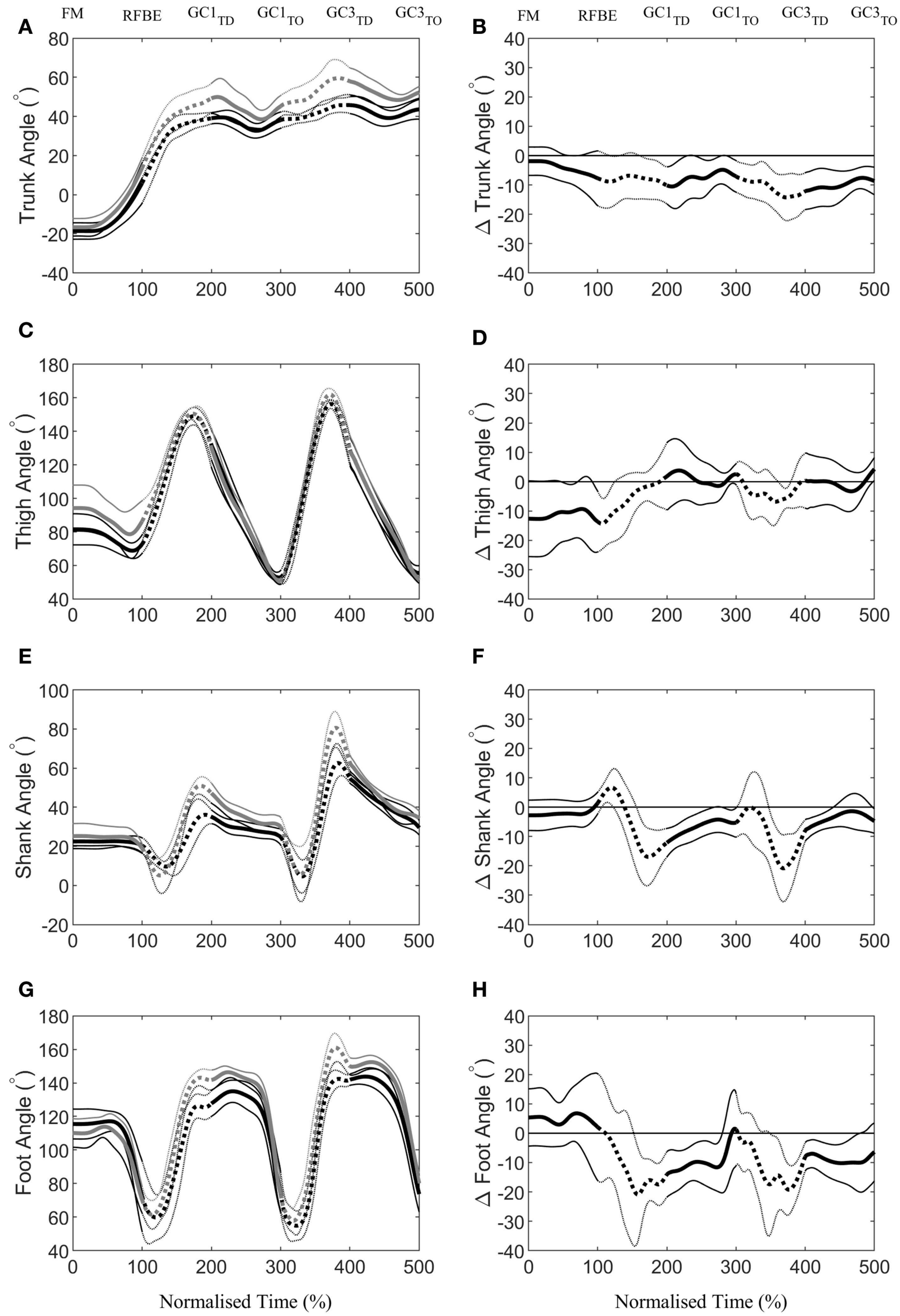

FIGURE 9 | Continuous segment angles (Mean ± SD) of the trunk **(A)**, thigh **(C)**, shank **(E)**, and foot **(G)**, for sprinters (black) and hurdlers (grey), and corresponding differences **(B,D,F,H)** between the sprinters, and hurdlers (thick line), and 95% confidence interval (thin line). Positive differences indicate a greater value for sprinters, and negative differences a greater value for hurdlers. Sections where the confidence interval bands do not cross zero (x-axis) represent clear differences between groups. Solid lines represent the double-leg push phase in the blocks, and first and, third ground contacts, whereas dashed lines represent the first and second swing phases of the rear leg, with key events related to the rear leg in the blocks marked above the figure. For definitions of segment angles (see **Figure 2**).

lead and trail legs further, but it is an interesting avenue for future research, especially given the asymmetrical and repetitive nature of the hurdle-unit gait cycle.

The hurdlers used a larger block spacing than the sprinters (difference −0.10 m, −0.17 to −0.04, large effect, **Table 1**). According to block spacing classifications typically used, the hurdlers' mean spacing was medium, whilst the sprinters' was bunched (Slawinski et al., 2012). Despite the effects of relative block spacing being well-known (e.g., Henry, 1952; Slawinski et al., 2012), and supported in this study with greater spacings

TABLE 3 | Joint and segment angles in the set position, and range of motion throughout initial acceleration for sprinters and hurdlers (Mean ± SD).

Variable	Sprinters	Hurdlers	Difference	95% Confidence interval	Effect size (*d*)
Set position angle (°)					
Rear hip	80 ± 9	69 ± 11	11	0 to 22	−1.10^{M}
Rear knee	121 ± 10	111 ± 19	10	−7 to 27	−0.66^{M}
Rear ankle	87 ± 9	95 ± 11	−8	−20 to 3	−0.80^{M}
Rear thigh	82 ± 9	94 ± 14	−13	−26 to 0	−1.10^{M}
Rear shank	22 ± 2	25 ± 6	−3	−8 to 2	−0.60^{M}
Rear foot	116 ± 9	110 ± 9	−5	−4 to 15	0.61^{M}
Front hip	45 ± 7	35 ± 8	10	2 to 18*	1.41^{L}
Front knee	93 ± 5	90 ± 10	3	−6 to 11	0.35^{S}
Front ankle	102 ± 8	98 ± 11	4	−6 to 15	0.46^{S}
Front thigh	118 ± 6	126 ± 12	−8	−19 to 2	−0.89^{M}
Front shank	31 ± 5	36 ± 5	−6	−11 to 0	1.13^{M}
Front foot	108 ± 7	118 ± 8	−10	−18 to −2*	1.32^{L}
Trunk	−19 ± 4	−17 ± 4	−2	−7 to 3	−0.44^{S}
Range of motion (°)					
FM - RFBE					
Hip	33 ± 18	38 ± 9	−5	−21 to 11	−0.33^{S}
Knee	7 ± 11	2 ± 17	5	−11 to 21	0.36^{S}
Ankle	41 ± 14	34 ± 13	7	−8 to 23	0.55^{S}
Trunk	25 ± 10	30 ± 7	−6	−15 to 4	−0.68^{M}
Thigh	−9 ± 10	−8 ± 13	−1	−14 to 12	−0.09ND
Shank	−2 ± 2	−6 ± 5	4	0 to 9	1.03^{M}
Foot	−43 ± 16	−40 ± 12	−3	−19 to 13	−0.23^{S}
FM-GC1$_{TD}$					
Trunk	59 ± 6	67 ± 10	−8	−17 to 1	0.99^{M}
GC1$_{TD}$ - GC1$_{TO}$					
Hip	78 ± 11	76 ± 8	2	−9 to 13	0.24^{S}
Knee	69 ± 13	62 ± 4	6	−5 to 17	0.62^{M}
Ankle	43 ± 11	51 ± 6	−8	−19 to 2	−0.92^{M}
Trunk	−1 ± 3	−4 ± 4	3	−1 to 7	0.91^{M}
Thigh	−79 ± 11	−80 ± 11	1	−11 to 13	0.07ND
Shank	−10 ± 5	−17 ± 8	7	0 to 14	1.06^{M}
Foot	−53 ± 14	−68 ± 11	15	1 to 30*	1.19^{M}
GC3$_{TD}$ - GC3$_{TO}$					
Hip	71 ± 11	72 ± 9	0	−12 to 11	−0.05ND
Knee	48 ± 8	49 ± 4	−1	−8 to 7	−0.11ND
Ankle	43 ± 8	41 ± 5	2	−6 to 9	0.23^{S}
Trunk	−2 ± 2	−6 ± 7	3	−2 to 9	0.74^{M}
Thigh	−73 ± 10	−77 ± 9	4	−7 to 15	0.42^{S}
Shank	−25 ± 3	−29 ± 7	3	−3 to 9	0.62^{M}
Foot	−68 ± 8	−70 ± 9	2	−8 to 11	0.20^{S}

*Differences are calculated as sprinters minus hurdlers, so negative values represent values for hurdlers being greater than sprinters. *Represents where the confidence interval for the between group comparison does not cross zero (Altman and Gardner, 2000). Effect size scale (Hopkins et al., 2009): No Difference (ND) = < 0.20; Small (S) = ≥ 0.20 to < 0.60; Moderate (M) = ≥ 0.60 < 1.20; Large (L) = ≥ 1.20 to < 2.00; Very Large (VL) = ≥ 2.00 to < 4.00; Extremely Large (EL) = ≥ 4.00.*

leading to longer push-phase times, the absolute positioning of the blocks from the start line has received little attention in the biomechanics research literature (Schot and Knutzen, 1992). Coaching literature has identified that hurdlers tend to place starting blocks closer to the start line than sprinters, but that this has negative consequences for performance (Mann and Murphy, 2018). In this study, the hurdlers' medium block spacing combined with the front block being closer to the start line (**Table 1**) led to relatively more flexed hip angles in the set position (front hip difference 10°, 2 to 18, large effect; rear hip difference 11°, 0 to 22, medium effect; **Figure 4**, **Table 3**). The net effect would have led to a greater extensor angular velocity of the front hip in the hurdlers, particularly during the single-leg push phase (Slawinski et al., 2013), which therefore

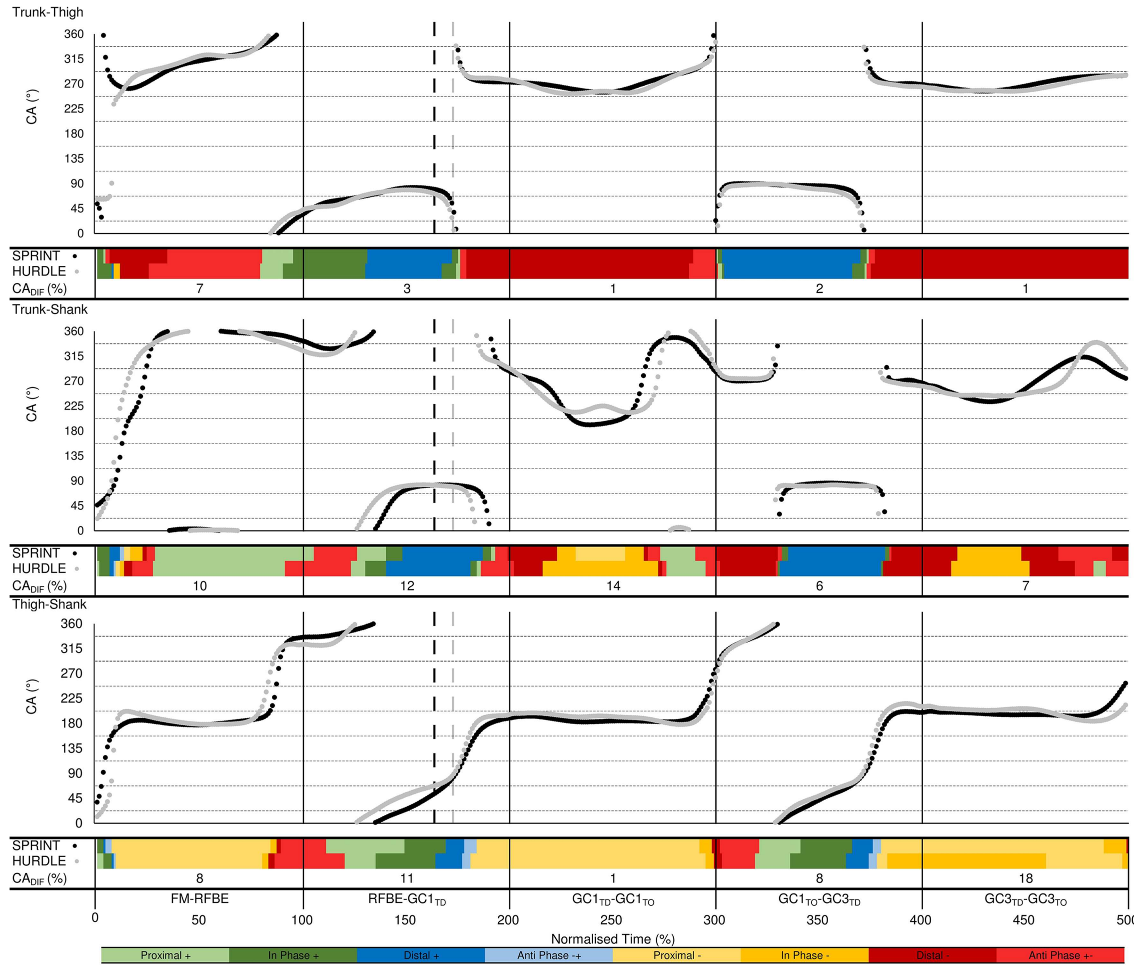

FIGURE 10 | Trunk-thigh (top), trunk-shank (middle), and thigh-shank (bottom) coupling angle-normalised time profiles for the sprint (black dots) and hurdle (grey dots) groups throughout each key phase of start and initial acceleration related to the rear leg in the blocks. Colour profiles represent coupling angle classification at each instance across the normalised time cycle (see **Figure 3B**). The overall difference score (CA_{DIF}) in coordination patterns between the sprint and hurdle groups is shown beneath each colour profile. Group mean instances of FFBE are indicated by black (sprint) and grey (hurdle) vertical dashed lines.

would have increased the vertical displacement of the CM and shoulder joint centres (**Figures 6A**, **7A**, respectively) more so in the hurdlers than sprinters. Analysis of trunk-thigh couples in the block phase showed an earlier onset of anti phase (+−) coordination (**Figure 10**), supporting the finding that hurdlers started to raise their trunk and CM earlier in the block phase than sprinters. Indeed, the biggest differences seen in the raising of the CM between hurdlers and sprinters occurred during the block phase, and likely come as a direct consequence of the differences in body orientations in the set position.

During the double-leg push phase the hurdlers as a group were clearly more variable than the sprinters in the amount that they raised the CM, and hip and knee joint centres, but clearly less variable in the amount that they raised their shoulder joint centre (**Figures 6**, **7**). This suggests a more variable response in the lower limb within the hurdlers, between different athletes, and highlights individual variations in the responses to the task. It is important for coaches to note that despite the consistent extent to which the hurdlers raised their shoulders during the double leg push phase, the manner in which this was controlled by the distal segments was much more variable.

Continuous segmental data (**Figures 4**, **8**, **9**) revealed that the hurdlers had more vertically orientated trunk and shank segments, and more horizontally orientated foot segments, than sprinters for periods in late swing and early stance around both $GC1_{TD}$ and $GC3_{TD}$. At each of the subsequent take-off events the differences in trunk, shank and foot angles between hurdlers and sprinters, whilst still clear, had reduced in magnitude (**Figure 9**). It therefore appears that these differences tend to accumulate during the longer flight phases in the hurdlers (**Table 1**), but then during the ground contact phases the hurdlers bring their segment orientations back towards those adopted by the sprinters (**Figure 9**). It is likely that the differences in segment angles combined with the greater stature of the hurdlers combine to provide the visual impression of a more upright stance in the hurdlers, particularly at touchdown events.

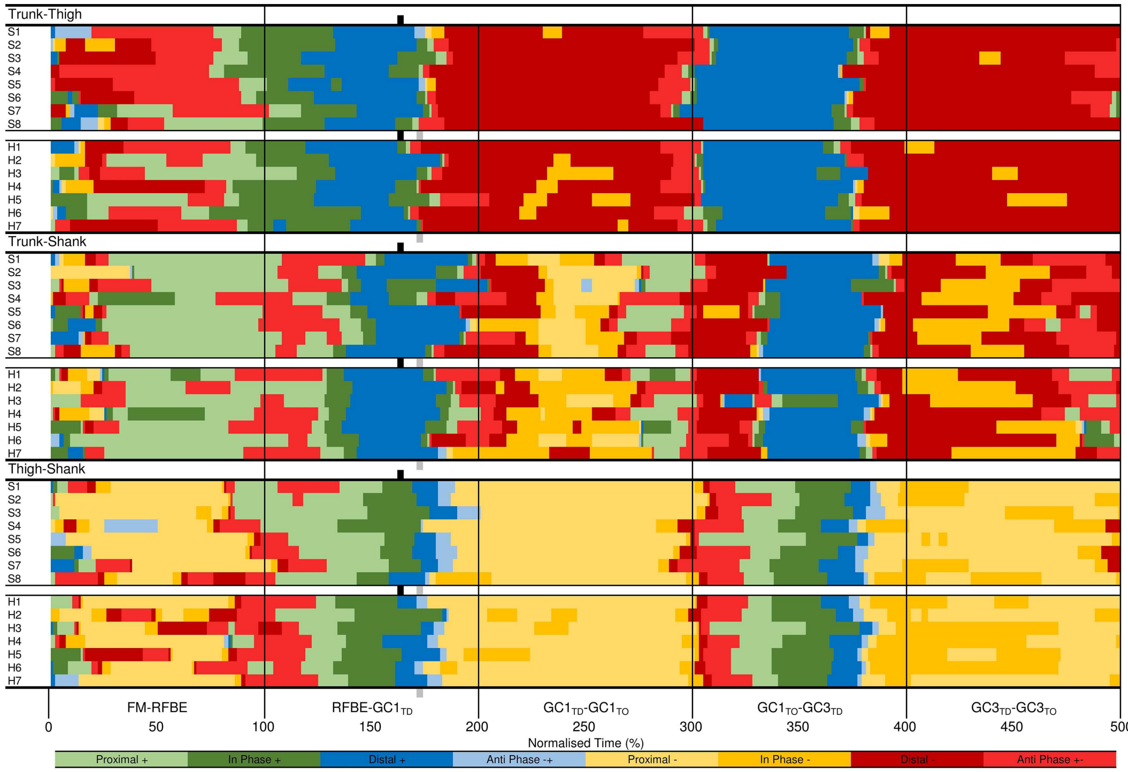

FIGURE 11 | Individual coordination profiles for the trunk-thigh (top), trunk-shank (middle), and thigh-shank (bottom) couples, throughout each key phase of start and initial acceleration related to the rear leg in the blocks. Colour profiles represent coupling angle classification at each instance across the normalised time cycle (see **Figure 3B**). Group mean instances of FFBE are indicated by black (sprint) and grey (hurdle) shading surrounding each group of individual athletes.

One key novel aspect of the current study was the complimentary nature of both qualitative and quantitative analysis of coordination, utilising popular 'binning' approaches (Silvernail et al., 2018) to visualise local and global similarities and differences in inter-segmental coordination in this unique sample of world-class athletes. The largest inter-group and inter-individual differences in coordination were observed soon after FM. As coordination variability has been shown to increase during changes to the state of the system (Heiderscheit et al., 2002), it could be theorised that the abrupt state change at FM contributed to the observed inter-group and inter-individual differences. In addition, the differences in the set position between athletes might have dictated initial coordination of the system, as shown by Gheller et al. (2015) who found that starting knee angle influenced coordination patterns during vertical jumps. The reduction in inter-individual differences after the initial part of the double-leg push phase could be indicative of self-organisation towards task-specific coordinative structures (Newell, 1986). However, it should be recognised that artefacts when consecutive data points are in close proximity (Heiderscheit et al., 2002) could also have influenced the initial inter-group and inter-individual differences in coordination at this early stage of the movement.

The nature of the data presented in this study, captured *in situ* in the world's best sprinters and hurdlers during the finals of the IAAF World Indoor Championships ensured that the ecological validity of the analysis conducted here was maintained in an exceptional manner. Indeed, the 60 m final included three of the fastest twenty times run in the history of the event. The very nature of this maintenance of ecological validity means that the sample sizes were small. However, the populations of the very best athletes in the world in any individual event are by definition small, and this study provides a comprehensive analysis of the mechanisms for the translation of the CM in this world-class sample. In doing so, it therefore addresses a significant gap in the biomechanics research literature. Further, studies of sprint hurdle biomechanics have generally focused on the hurdle clearance and three-step inter-hurdle cycle (e.g., Mann and Herman, 1985a; McDonald and Dapena, 1991; Salo et al., 1997). To the authors' knowledge this is the first study that has investigated the start and initial acceleration phase in elite high hurdlers, as well as being the first to apply coordination analyses to the start and initial acceleration phase of a sprint. Data presented here have shown that the biggest differences in the raising of the CM occurred during the single-leg push phase in the blocks. Future research should therefore additionally consider the role of the front leg in the blocks, that might reveal interesting additional insights into the mechanisms utilised by sprinters and hurdlers.

Coaching Implications

The similarities that were shown between the sprinters and hurdlers, despite the differing task constraints being faced by the athletes, were the most striking feature of this analysis. Overall, the response to the task to accelerate the CM in a horizontal direction was primarily the same across the two events, which challenges current thinking. The key differences that did occur came primarily from the initial body positions in the set position, so there should be some consideration for an individual approach to block set up by coaches and athletes. Once the push phase in the blocks began, there was clearly a relatively common pattern of coordination across all athletes. This overall consistent organisation of movement during the start and initial acceleration phase is an important consideration for coaches, and needs to be maintained even when accounting for individual factors that may influence performance such as stature or strength. The hurdlers as a group were more variable than sprinters in the manner in which they raised their lower body segments in the block phase, but then also used the following ground contact phases to converge their segment orientations back towards those adopted by the sprinters. It may therefore be that small visual differences in orientations that might be apparent at touchdown events should not be of major concern, and are typically overcome by hurdlers during the subsequent ground contact phase.

The fact that all seven hurdlers studied here chose to adopt a seven-step approach to the first hurdle meant that a direct comparison of the differences between seven- and eight-step approaches was not possible. Additional work is no doubt required to address the implications of any differences between these two approach strategies. Nonetheless, the data presented here provides an important underpinning to the coaching literature, and reveals that even when high-hurdlers adopt a seven-step approach to the first hurdle, there are many similarities between the techniques they adopt and those of their sprint counterparts.

CONCLUSION

This novel study was successful firstly in quantifying and explaining the start and initial acceleration technique of the world's best male sprinters and hurdlers *in situ* in an elite competition environment, and secondly in elucidating the similarities in the mechanisms by which sprinters and hurdlers translate their CM during the start and initial acceleration phases. Coordination patterns adopted by sprinters and hurdlers were similar throughout the start and initial acceleration phases, and differences in CM raising generally occurred as a result of small differences that were present from block set-up. This study has generated an exceptional and significant data set, and the analysis presented here will become a primary source of reference for those wanting to further explore the start and initial acceleration phase in both sprinters and hurdlers as a means of optimising performance. The findings from this study contribute new conceptual understanding of the mechanisms that underpin start and initial acceleration performance for scientists, coaches and athletes.

DATA AVAILABILITY

The datasets generated for this study will not be made publicly available in order to avoid identifying individual athletes.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by (1) IAAF obtained signed Athlete Acknowledgment and Agreement Forms from the athletes to use their moving images. (2) The study was approved by the Leeds Beckett University Ethics sub-committee (School local approval by Research Ethics Coordinator). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

IB, ABr, HL, GP, SM, P-JV, JW, and ABi conceived and designed the study. GP, BH, CT, LP, JW, and ABi performed data collection. IB, ABr, HL, BH, CT, LP, JW, and ABi processed data. IB, ABr, HL, MW, GP, JW, and ABi interpreted the results of the research. IB and ABr drafted the manuscript. IB, ABr, and HL prepared tables and figures. IB, ABr, HL, MW, GP, BH, CT, LP, SM, P-JV, JW, and ABi edited, critically revised, and approved the final version for submission.

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ORIGINAL RESEARCH
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The Effect of EVA and TPU Custom Foot Orthoses on Running Economy, Running Mechanics, and Comfort

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Custom made foot orthoses (CFO) with specific material properties have the potential to alter ground reaction forces but their effect on running mechanics and comfort remains to be investigated. We determined if CFO manufactured from ethyl-vinyl acetate (EVA) and expanded thermoplastic polyurethane (TPU) materials, both compared to standardized footwear (CON), improve running economy (RE), running mechanics, and comfort at two running speeds. Eighteen well-trained, male athletes ran on an instrumented treadmill for 6 min at high (HS) and low (LS) speeds corresponding to and 15% lower than their first ventilatory threshold (13.8 ± 1.1 and 11.7 ± 0.9 km.h^{-1}, respectively) in three footwear conditions (CON, EVA, and TPU). RE, running mechanics and comfort were determined. Albeit not reaching statistical significance ($P = 0.11$, $\eta^2 = 0.12$), RE on average improved in EVA (+2.1 ± 4.8 and +2.9 ± 4.9%) and TPU (+0.9 ± 5.9 and +0.9 ± 5.3%) compared to CON at LS and HS, respectively. Braking force was decreased by 3.4 ± 9.1% at LS and by 2.7 ± 9.8% at HS for EVA compared to CON ($P = 0.03$, $\eta^2 = 0.20$). TPU increased propulsive loading rate by 20.2 ± 24 and 16.4 ± 23.1% for LS and HS, respectively compared to CON ($P = 0.01$, $\eta^2 = 0.25$). Both arch height ($P = 0.06$, $\eta^2 = 0.19$) and medio-lateral control ($P = 0.06$, $\eta^2 = 0.16$) showed a trend toward improved comfort for EVA and TPU vs. CON. Compared to shoes only, mainly EVA tended to improve RE and comfort at submaximal running speeds. Specific CFO-related running mechanical adjustments included a reduced braking impulse occurring in the first 25% of contact time with EVA, whereas wearing TPU increased propulsive loading rate.

Keywords: orthotics, material resilience, economy of locomotion, gait, running, kinetics

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INTRODUCTION

Custom foot orthoses (CFO) are increasingly used to alter the magnitude and resultant direction of ground reaction forces (GRF) under the foot by modifying foot-surface interaction. In previously injured athletes, for instance after suffering a lateral ankle sprain, wearing CFO decreased the inversion moment around the subtalar joint axis (Kirby, 2017). The magnitude of the reduction in subtalar joint inversion moment, ultimately altering GRF production during locomotion, directly depends on the amount of customization by molding and/or posting (McCormick et al., 2013). This individualized surface geometry, in combination with materials used, also likely determine comfort, cushioning, and bending stiffness (Mundermann et al., 2003a,b; Kirby and Werd, 2014).

Running Economy (RE) is one important factor, in addition to maximal oxygen uptake (VO_{2max}) and the fraction of VO_{2max} that can be sustained, which determines exercise capacity (Karp, 2008; Shaw et al., 2013). Efficiency of elastic return through foot-surface interaction and the amount of GRFs produced are important modifiable biomechanical factors determining RE (Arellano and Kram, 2014; Barnes and Kilding, 2015; Moore, 2016). There is conflicting evidence in the literature regarding the effect CFO have on RE. Higher VO_2 values were reported in runners with a history of running related injuries both at ∼14 km.h^{-1} and ∼16 km.h^{-1} when using CFO compared to control (i.e., without CFO), while flexible and semi-rigid CFO had similar effects (Hayes et al., 1983). Contrastingly, RE on average improved by ∼8% when male endurance trained runners ran at five preset speeds ranging ∼11–15 km.h^{-1}, while wearing CFO compared to a shoe fitted support (Burke and Papuga, 2012). In these aforementioned studies, however, stride pattern was not characterized to offer a possible biomechanical explanation for CFO-related adjustments in RE. Additionally, previous literature often lacks reporting the precise nature of customization (e.g., type of negative foot model, amount and area of molding and/or posting, materials used, weight of different footwear conditions), which limits strength of comparison between available studies (Fuller et al., 2015). The use of different running shoes between runners (Burke and Papuga, 2012) and set (i.e., absolute) running speeds for a range of runners with rather different levels of overall aerobic fitness (Hayes et al., 1983; Burke and Papuga, 2012) also participate to increase interindividual variability in the response to a CFO intervention.

CFO might have the potential to improve RE through their shape and material characteristics. It is likely (but unknown) that more favorable running mechanics could be attributed to these surface characteristics. A modified stride mechanical pattern, for instance by decreasing vertical impact forces, peak medial–lateral force and horizontal braking GRF and/or by increasing horizontal propulsive GRF, has the potential to alter RE (Moore, 2016). Compared to running in sport shoes only, MacLean et al. (2008) observed that the addition of CFO decreases vertical impact peak force (∼6%) and vertical loading rate (∼12%), yet the effect on RE was not reported in this study. While the effects of CFO on vertical GRF are relatively well-described, there is comparatively less information on the impact this may have on the horizontal GRF component and its relationship with RE. Chang and Kram (1999) identified that, for well-trained recreational runners running at ∼12 km.h^{-1}, the metabolic cost for generating horizontal forces is about four times higher than for vertical forces. This suggests that the collection and analysis of horizontal GRF should be considered when evaluating the effects CFO on RE.

Materials used to produce CFO vary widely. Flexible shank-dependent CFO are commonly made of EVA or polyurethane foams. According to Zeintl (2018), EVA has a 37% resilience elasticity using a standard ball rebound lab test. Compared to EVA, expanded thermoplastic polyurethane (TPU) (Infinergy®, BASF, Germany) achieves a rebound of 55%. When used in the midsole of a running shoe, TPU was associated with a ∼4% improvement in RE when compared to running with conventional running shoes (Sinclair et al., 2016). Even though no reporting was made on running mechanics in this study, Worobets et al. (2014) mechanically tested the energy loss using actuated compression testing and found hysteresis values of 31.3–32.3 and 20.9–22.3% for EVA and TPU midsole shoes, respectively. This suggests, but is yet to be verified, that increases in resilience might lie at the basis of its positive effect on RE.

Material characteristics (i.e., density and stiffness) can strongly influence the perception of comfort and is key when deciding to keep wearing CFO or not. Comfort is defined by individual preference and is in turn influenced by many factors such as perception of pain, fatigue, and possibly running speed (Mundermann et al., 2003b). Early comfort studies showed that single verbal ratings (Milani et al., 1995) or even a single five point Likert scale (Hennig et al., 1996) proved not sensitive and provided unreliable results. An assessment tool for measuring comfort, focusing on a range of perceptions (e.g., cushioning, amount of movement control) linked to specific foot sections (e.g., heel, midfoot, and forefoot of footwear and orthotics) was subsequently developed (Mundermann et al., 2002). Different items from this tool (overall comfort, heel cushioning and heel cup fit and medial-lateral control) correlated with improved RE (Burke and Papuga, 2012) when wearing CFO. However, the effect of specifically wearing EVA or TPU materials on comfort and how this relates to alterations in running mechanics and RE at different speeds is unknown.

The aim of this study was to determine the effect of CFO manufactured from EVA and TPU materials (identical shape but different resilience and stiffness characteristics), both compared to a control condition (shoes only), on measures of RE, comfort for different perceptions and locations under the foot (heel, medial arch and forefoot) and running mechanics with special reference to horizontal force production (e.g., braking and propulsive forces) when running at two individualized submaximal speeds. We first hypothesized that, compared to control, EVA and TPU materials would improve RE and increase comfort (for cushioning and control, in general and under the heel, arch and forefoot), due to more efficient running mechanics (e.g., lower vertical impact forces and loading rates, less mechanically-demanding forward-orientated forces). We further hypothesized that the magnitude of these changes will be larger while wearing CFO made of TPU compared to EVA due to the higher resilience material properties.

METHODS

Participants

Twenty-one male well-trained athletes (mean ± SD age, 38.9 ± 5.1 years; stature, 175.3 ± 5.8 cm; body weight, 74.9 ± 7.7 kg) were recruited for this study. They trained (running and swimming and/or cycling) on average 8.8 ± 3.7 h per week in the 3 months leading up to the data collection with an average weekly running distance of 37.6 ± 26.7 km. During training, participants spent on average 3.8 ± 2.6 h in low intensity, 2.7 ± 1.7 h in medium intensity, 2.2 ± 0.8 h in a high-intensity workout, with also 1.9 ± 1.3 h dedicated to resistance training. Three participants dropped out of the study, one for personal reasons, the second because he couldn't complete the full protocol, the third due to illness. In our final sample of eighteen participants, thirteen were rearfoot strikers, one was a midfoot striker and four were forefoot strikers at 10 km.h^{-1}. Two separate raters (KVA and OG) agreed on foot strike pattern, using sagittal plane video-analysis at the level of the foot at a sampling frequency of 240 Hz using an iPhone 6 (Apple, California, US). The participants had a foot structure of median (min, max) 7 (−6, +11) for the left and right foot, as determined by the Foot Posture Index FPI-6 that was scored after completing the last session (KVA). Reference values were labeled as normal (0 to +5), pronated (+6 to +9), highly pronated (10+), supinated (−1 to −4) and highly supinated (−5 to −12) (Redmond et al., 2006). Participants had no known history of cardiovascular, neurological, or orthopedic problems, were injury free for the 3 months leading up to the data collection and gave written informed consent prior to participation in the study. Ethical approval for the study was provided by the Anti-Doping Laboratory Ethics Committee in Qatar (IRB Application Number 2017000201) and was undertaken according to the principles outlined in the Declaration of Helsinki.

Experimental Protocol

Participants attended the lab on four separate occasions. The first visit aimed at determining the individual ventilatory threshold and corresponding running speed that was used for the three following intervention sessions. The remaining three visits consisted of running at two sub-maximal speeds in different footwear conditions. The second visit was the control session where participants ran with standardized (i.e., only shoe liner inserted) footwear (CON). During the third and fourth session CFO (EVA and TPU) were inserted bilaterally in participants shoes, before the warm-up and for the rest of the session, with the order of intervention randomized between sessions. Participants were asked to avoid strenuous exercise in the 12 h, as well as refrain from food and caffeine for 4 h preceding their visits to the laboratory and were encouraged to replicate their diet and training pattern for all visits. Laboratory conditions were similar throughout all running sessions (mean ± SD temperature 20.7 ± 0.2°C, relative humidity 60.4 ± 0.6%). Time of day was standardized for each participant over all sessions. The participants and the researcher who was directly involved in guiding the runners during the running protocol were visually blinded from the CFO materials.

Running Bouts

Incremental Test (Visit 1)

Each participant completed a continuous, maximal incremental running test. Briefly, participants started running at 9 km.h^{-1} with speed increases of 0.5 km.h^{-1} every 30 s. The test ended with voluntary exhaustion of the participants. Verbal encouragement was only given by the researcher guiding the runners throughout the session. Ventilatory threshold was determined using the criteria of an increase in minute ventilation (V_E)/Oxygen uptake (VO_2) with no increase in V_E/Carbon dioxide (VCO_2) and the departure from linearity of V_E (Davis, 1985).

Sub-maximal Runs (Visits 2, 3, and 4)

After a 10 min warm-up at 10 km.h^{-1}, followed by a 3 min break used to put on the mask to collect expired gases, participants ran two, 6-min trials: One at an intensity corresponding to the speed associated with the first ventilatory threshold (HS or high speed) and one at a speed 15% below the first ventilatory threshold (LS or low speed), with 3 min recovery in between. The order in which LS and HS conditions were applied was randomized across participants, but held constant for each individual throughout their sessions. The complete timing sequence from warm-up to finish was strictly controlled and guided by visual and verbal cues.

Footwear

During all running the participants used neutral like running shoes (Pearl Izumi N2v2, Colorado, US) with an average European shoesize of 43.6 ± 1.6. At the end of the second visit (control session using shoes with its original shoe liner), each participant received two pairs of CFO based on an individual non-weight bearing 3D scan of the foot using a Delcam iCube scanner (Elinvision, Karmelava, Lithuania) completed at the end of the first visit. CFO were designed by an experienced sport podiatrist with nearly 20 years of experience, using the Orthomodel Pro CAD software (Autodesk, California, USA). Briefly, scans were imported into the software, markers were placed over the heel, first- and fifth metatarsal and medial arch. A base model surface was adjusted to match the contour of the foot using cross-sectional views from the heel to the forefoot. The thickness of the orthotic was arbitrary set to 8 mm in an attempt to maximize the potential of the TPU beats inside the Infinergy® material (BASF, Ludwigshafen, Germany). All CFO were direct-milled out of EVA and TPU and manually finished to fit inside the shoes (**Figure 1**).

On initial fitting and again before the start of the third session (shoes with the first pair of CFO), participants were asked if the CFO were comfortable and if any adjustments were necessary. When adjustments were made (4 out of 18 participants), they

FIGURE 1 | Left: a pair of original liners (CON) of shoes, **Middle:** a pair of the custom Thermoplastic Poly-Urethane orthoses (TPU) and **Right:** a pair of custom Ethyl-Vinyl Acetate orthoses (EVA).

were done on both pairs of CFO to keep an identical shape. No additional adjustment in shape were made between the third and fourth sessions.

Wear-in time between the first and second intervention session was 4.5 ± 2.5 and 4.6 ± 2.8 days between the second and last intervention session. The weight of the three footwear conditions was on average 600.3 ± 32.0, 647.3 ± 36.0, and 681.1 ± 35.7 g for the shoes with its original liners (CON), with the custom EVA orthoses (EVA) and with the custom TPU orthoses (TPU), respectively.

Data Measure

Metabolic Card

A Jeager™ Oxycon Mobile cardio pulmonary exercise testing unit (Carefusion, Hoechberg, Germany) was used to record breath-by-breath and cardio-respiratory data. Prior to each session, calibration of gas sensor was completed for ambient air and a known gas mixture (16% O_2, 5% CO_2). Turbine was calibrated using a 3-Liter (±0.4%) syringe and automated High and Low flow ventilation. The metabolic cart was suspended from the ceiling next to participants, so they didn't have to support the additional weight of the system when running.

Instrumented Treadmill

An instrumented treadmill (ADAL3D-WR, Medical Developpement - HEF Tecmachine, France) was used for all running conditions (incremental test, constant speed running). Briefly, it is mounted on a highly rigid metal frame, set at 0°grade incline, fixed to the ground through four piezoelectric force transducers (KI 9077b; Kistler, Winterthur, Switzerland) and installed on a specially engineered concrete slab to ensure maximal rigidity of the supporting ground (Girard et al., 2017).

Data Analysis

Cardiorespiratory and Metabolic Variables

Breath-by-breath gas samples were first averaged every 15 s and subsequently expressed as the average of the last 2 min of each 6-min run. Oxygen uptake expressed in both absolute (VO_2 in $mL.min^{-1}$) and relative (RVO_2 in $mL.kg^{-1}.min^{-1}$) terms, V_E ($L.min^{-1}$), breathing frequency (BF) ($breaths.min^{-1}$), tidal volume (VT) (L) were determined. Heart rate (HR) ($beats.min^{-1}$) was continuously measured by short-range telemetry (Polar, Kempele, Finland). Running Economy (RE) was calculated as the VO_2 per bodyweight over speed, expressed in milliliters of oxygen consumed per kilogram per kilometer ($mL.kg^{-1}.km^{-1}$).

Kinetic Variables

Over the last 2 min of each 6-min run, three-dimensional ground reaction force was continuously sampled at 1,000 Hz. Ten continuous steps recorded at 4 min 15 s, 4 min 45 s, 5 min 15 s, and 5 min 45 s were subsequently averaged for final analysis. After appropriate filtering (Butterworth-type 30 Hz lowpass filter), data were averaged over the support phase of each step (vertical force above 30 N). Further main spatio-temporal variables: contact time (s), flight time (s), step frequency (Hz) were reported. Vertical stiffness (K_{vert} in $kN{\cdot}m^{-1}$) was calculated as the ratio of peak vertical forces (F_{zmax} in N) to the maximal vertical downward displacement of center of mass (Δz in m), which was determined by double integration of vertical acceleration of center of mass over time during ground contact (Cavagna, 1975; Morin et al., 2005). Leg stiffness (K_{leg} in $kN{\cdot}m^{-1}$) was calculated as the ratio of F_{zmax} to the maximum leg spring compression (ΔL) ($\Delta z + L0 - \sqrt{L0^2} - [0.5 \times \text{running speed} \times \text{contact time}]^2$, in m), both occurring at mid-stance (Morin et al., 2005). Initial leg length (L0, great trochanter to ground distance in a standing position) was determined from participant's stature as $L0 = 0.53 \times$ stature (Morin et al., 2005). Finally, vertical mean/peak loading rate was calculated as the mean/peak value of the time-derivate of vertical force signal within the first 50 ms of the support phase, and expressed in $N{\cdot}s^{-1}$(De Wit et al., 2000).

Also, horizontal forces were analyzed with main variables defined as: peak braking and peak propulsive forces (BW) and the timing (ms) when these events occurred from initial contact; the duration of braking and propulsion forces (ms); the braking and push-off impulse ($m.s^{-1}$) and instantaneous loading rates ($N.s^{-1}$).

RPE and Comfort Measures

Rating of perceived exertion (RPE) was measured every 30 s during the continuous incremental test and the two steady-state runs using the 6-20 Borg scale (Borg, 1982). Within the first minute after finishing HS and LS runs, a global (6-min run) RPE value was collected.

A modified version of the footwear comfort assessment tool, developed and tested on reliability by Mundermann et al. (2002), was used to assess comfort associated with wearing each footwear condition using an iPad mini (Apple, California, US). This scale was used in previous studies to assess footwear comfort (McPoil et al., 2011; Burke and Papuga, 2012). For this study, only six of the nine items ("overall comfort," "heel cushioning," "forefoot cushioning," "medio-lateral control," "arch height," and "heel cup fit") were scored on a digital, 150 mm VAS scale where 0 was defined as "not comfortable at all" and 150 "most comfortable condition imaginable."

Statistical Analysis

All physiological, mechanical and perceptual dependent variables collected while running in the three footwear conditions over two speeds (HS, LS) were compared using a two-way ANOVA with repeated measures [Condition (CON, EVA, TPU) × Speed (LS, HS)] after confirming a normal distribution (Shaphiro-Wilk), homogeneity (Levene's), and sphericity (Mauchley's). A Greenhouse-Geisser correction was performed to adjust the degree of freedom if an assumption was violated, while a Šídák *post hoc* multiple comparison was performed if a significant main effect was observed for condition and an LSD *post hoc* comparison for speed. Partial eta-squared were calculated as a measure of effect size, with values of 0.01, 0.06, and >0.14 considered as small, medium and large, respectively (Cohen, 1988).The level of significance was set at $P \leq 0.05$. All statistical analyses were performed in IBM® SPSS® Statistics for Windows v.24 (IBM Corp., Armonk, NY, US).

TABLE 1 | Changes in cardiorespiratory parameters for shoe only (CON), shoe with Ethyl-Vinyl Acetate orthotic (EVA), and shoe with Thermoplastic Poly-Urethane orthotic (TPU) conditions at low and high speeds.

Parameters	Low speed			High speed			ANOVA *P*-value (η^2)		
	CON	EVA	TPU	CON	EVA	TPU	C	S	I
HR (beats.min^{-1})	154.9 ± 14.9	154.4 ± 12.9	152.7 ± 13.6*	164.3 ± 13.5	162.9 ± 12.6	161.7 ± 12.9*	**0.04** (0.17)	**0.01** (0.38)	0.57 (0.03)
RE (mL.kg^{-1}.km^{-1})	191 ± 11	187 ± 14	190 ± 12	190 ± 11	185 ± 14	188 ± 11	0.11 (0.12)	0.11 (0.14)	0.53 (0.04)
RVO_2 (mL.kg^{-1}.min^{-1})	37.60 ± 3.36	36.79 ± 3.57	37.26 ± 3.81	43.73 ± 4.01	42.48 ± 4.51	43.39 ± 4.98	0.11 (0.12)	**<0.001** (0.96)	0.28 (0.07)
VO_2 (mL.min^{-1})	2808 ± 351	2766 ± 380	2784 ± 390	3265 ± 405	3190 ± 425	3238 ± 448	0.18 (0.10)	**<0.001** (0.96)	0.29 (0.07)
VE (L.min^{-1})	77.9 ± 11.2	77.7 ± 11.4	76.7 ± 10.4	100.9 ± 15.6	100.7 ± 15.2	99.8 ± 15.2	0.60 (0.03)	**<0.001** (0.95)	1.00 (0.00)
BF (breaths.min^{-1})	38.12 ± 6.22	38.88 ± 7.37	38.62 ± 7.15	42.59 ± 6.83	44.91 ± 10.73	44.46 ± 8.26	0.15 (0.11)	**<0.001** (0.65)	0.48 (0.04)
VT (L)	2.08 ± 0.40	2.04 ± 0.48	2.06 ± 0.47	2.39 ± 0.43	2.31 ± 0.57	2.20 ± 0.48	0.21 (0.09)	**<0.001** (0.85)	0.39 (0.05)

*Values are mean ± SD. C, S, and I respectively refer to ANOVA main effects of condition, speed and interaction between these two factors with P-value and partial eta-squared (η^2) in parentheses. HR, Heart rate; RE, Running economy; RVO_2, Oxygen uptake relative to bodyweight; VO_2, Absolute oxygen uptake; VE, Minute ventilation; BF, Breathing frequency; VT, Tidal volume. Bold values indicate statistically significant findings. *Significantly different from CON ($P \leq 0.05$).*

RESULTS

The incremental test lasted on average 9.3 ± 1.6 min and participants ventilatory threshold was reached at a running speed of 13.8 ± 1.1 km.h^{-1} (corresponding to 73.5 ± 3.3% of the maximal reached speed) and labeled HS. The LS was 15% slower corresponding to an average running speed of 11.7 ± 0.9 km.h^{-1}.

Descriptive statistics are presented as mean values ± SD (**Tables 1–3**). Albeit not reaching statistical significance ($P = 0.11$, $\eta^2 = 0.12$), RE on average improved in EVA (+2.1 ± 4.8 and +2.9 ± 4.9%) and TPU (+0.9 ± 5.9 and +0.9 ± 5.3%) compared to CON at LS and HS, respectively (**Figure 2**). There was a statistically significant main effect of the condition on HR ($P = 0.04$, $\eta^2 = 0.17$) with higher HR and values in CON compared to the other two conditions. No significant speed × condition interaction was found ($P \geq 0.28$) for any cardio-respiratory variable (**Table 1**).

Almost all examined kinetic variables (except braking loading rate and leg stiffness) increased significantly from LS to HS ($P \leq 0.05$), irrespective of condition (**Table 2**). A significant main condition effect was noted for 9 out of 18 variables studied: contact time ($P = 0.01$, $\eta^2 = 0.28$), vertical peak loading rate ($P \leq 0.001$, $\eta^2 = 0.32$), vertical mean loading rate ($P = <0.001$, $\eta^2 = 0.52$), peak braking force ($P = 0.03$, $\eta^2 = 0.20$), peak propulsive force ($P = 0.03$, $\eta^2 = 0.23$), time peak braking force ($P \leq 0.001$, $\eta^2 = 0.55$), time peak propulsive force ($P \leq 0.001$, $\eta^2 = 0.37$), propulsive phase duration ($P \leq 0.001$, $\eta^2 = 0.30$), propulsive loading rate ($P = 0.01$, $\eta^2 = 0.25$). A significant interaction was found for braking impulse ($P \leq 0.05$, $\eta^2 = 0.17$) only.

Of all the subjective measures (**Table 3**), only RPE displayed a statistically significant large main effect of speed ($P < 0.001$, $\eta^2 = 0.77$), where higher RPE values were recorded for HS vs. LS. A trend toward improved awareness for arch height comfort was found ($P = 0.06$, $\eta^2 = 0.19$) for both EVA and TPU conditions compared to CON. Also, medio-lateral control ($P = 0.06$, $\eta^2 = 0.16$) was rated as more comfortable for both orthotic conditions compared to CON. Relative average changes (% ± SD) between the three conditions for the most important metabolic, kinetic measures are summarized in **Figure 3**.

DISCUSSION

The first hypothesis is only partially accepted as EVA improves RE (albeit not significantly) and increases comfort (for cushioning and control, in general and under the heel, arch, and forefoot), in line with more favorable running mechanics (decreasing braking forces) compared to the control condition. The second hypothesis is rejected as the magnitude of these changes was not larger for the higher resilient TPU in comparison to EVA. A unique aspect to this study was also to highlight favorable changes in running mechanics while wearing CFO, yet with material-specific effects. In summary, RE and comfort tended to be improved while wearing either EVA or TPU in reference to CON (with larger effects for the former) but this was not achieved through similar adjustments in running mechanics.

Running Economy

We reported improved RE ($P = 0.11$, $\eta^2 = 0.12$) mainly when using EVA (+2.1 ± 4.8 and +2.9 ± 4.9%), at HS and LS respectively, compared to CON ($P = 0.11$, $\eta^2 = 0.12$). The positive effect of TPU on RE (+0.9 ± 5.9 and +0.9 ± 5.3%), at HS and LS respectively, is considered as negligible. Similarly to EVA, improved RE of at least ∼3% was found by Burke and Papuga (2012) for male participants running at corresponding speeds ranging ∼11–15 km.h^{-1} using CFO (Ultrastep®). The larger effect of EVA vs. TPU on RE could be explained by the overall increase of footwear stiffness. With the introduction of CFO, the longitudinal bending stiffness of the footwear (shoe + CFO) would be higher (Levine, 2010), while this effect was probably larger for EVA in reference to TPU (both larger than CON). Reportedly, increases in footwear midsole bending stiffness in the range 6–8% improves RE by 1% (Roy and Stefanyshyn, 2006). Furthermore, lower values observed for RVO_2 in TPU compared to EVA might be attributed to a higher overall average mass (+34 g) of TPU. This has been described to be detrimental for RE (Hoogkamer et al., 2018). The higher weight and flexibility of TPU compared to EVA possibly dampens the beneficial properties improving RE.

TABLE 2 | Changes in running mechanics for shoe only (CON), shoe with Ethyl-Vinyl Acetate orthotic (EVA), and shoe with Thermoplastic Poly-Urethane orthotic (TPU) conditions at low and high speeds.

	Low speed			**High speed**			**ANOVA *P*-value (η^2)**		
	CON	**EVA**	**TPU**	**CON**	**EVA**	**TPU**	**C**	**S**	**I**
Spatiotemporal parameters									
Contact time (ms)	248 ± 19	248 ± 18	252 ± 20*	223 ± 17	225 ± 17	226 ± 17*	**0.01** (0.28)	**<0.001** (0.94)	0.08 (0.14)
Flight time (ms)	103 ± 19	104 ± 19	102 ± 17	117 ± 18	116 ± 19	117 ± 17	0.94 (0.00)	**<0.001** (0.89)	0.26 (0.08)
Step frequency (Hz)	2.86 ± 0.15	2.85 ± 0.13	2.83 ± 0.13	2.95 ± 0.15	2.94 ± 0.12	2.92 ± 0.13	0.25 (0.08)	**<0.001** (0.78)	0.92 (0.01)
Vertical forces									
Peak vertical force (BW)	2.54 ± 0.28	2.49 ± 0.25	2.49 ± 0.22	2.69 ± 0.27	2.62 ± 0.27	2.65 ± 0.24	0.11 (0.13)	**<0.001** (0.81)	0.54 (0.04)
Vertical peak loading rate (BW.s^{-1})	79.0 ± 17.4	80.2 ± 17.2	73.2 ± 14.9*†	95.4 ± 19.9	94.7 ± 20.9	89.3 ± 18.4*†	**<0.001** (0.32)	**<0.001** (0.88)	0.34 (0.07)
Vertical mean loading rate (BW.s^{-1})	51.1 ± 11.3	52.7 ± 11.0	44.4 ± 8.2*†	62.3 ± 13.8	62.4 ± 14.0	55.0 ± 10.6*†	**<0.001** (0.52)	**<0.001** (0.88)	0.28 (0.08)
Horizontal forces									
Peak braking force (BW)	−0.52 ± 0.11	−0.50 ± 0.11	−0.54 ± 0.10†	−0.59 ± 0.11	−0.59 ± 0.13	−0.60 ± 0.11†	**0.03** (0.20)	**<0.001** (0.87)	0.18 (0.10)
Peak propulsive force (BW)	0.34 ± 0.06	0.32 ± 0.05	0.32 ± 0.05	0.41 ± 0.06	0.39 ± 0.07	0.39 ± 0.06*	**0.03** (0.23)	**<0.001** (0.96)	0.28 (0.07)
Time peak braking force (ms)	61 ± 5	61 ± 7	64 ± 8*†	57 ± 8	58 ± 7	60 ± 8*†	**<0.001** (0.55)	**<0.001** (0.44)	0.37 (0.06)
Time peak propulsive force (ms)	184 ± 15	184 ± 15	188 ± 17*†	167 ± 14	168 ± 14	169 ± 15*†	**<0.001** (0.37)	**<0.001** (0.87)	0.09 (0.14)
Braking phase duration (ms)	120 ± 11	119 ± 10	121 ± 11	109 ± 9	108 ± 8	110 ± 8	0.13 (0.12)	**<0.001** (0.82)	0.22 (0.09)
Propulsive phase duration (ms)	128 ± 11	129 ± 10	131 ± 12*	114 ± 11	116 ± 12	116 ± 12*	**<0.001** (0.30)	**<0.001** (0.95)	0.43 (0.05)
Braking impulse (m.s^{-1})	0.24 ± 0.03	0.23 ± 0.03	0.24 ± 0.03	0.26 ± 0.03	0.25 ± 0.03	0.25 ± 0.03	0.21 (0.09)	**<0.001** (0.84)	**0.05** (0.17)
Propulsive impulse (m.s^{-1})	0.25 ± 0.03	0.24 ± 0.03	0.25 ± 0.03	0.27 ± 0.03	0.26 ± 0.03	0.26 ± 0.02	0.15 (0.12)	**<0.001** (0.81)	0.11 (0.14)
Braking loading rate (N.s^{-1})	33.33 ± 14.26	33.38 ± 13.67	32.90 ± 12.91	34.66 ± 15.38	34.56 ± 14.76	34.57 ± 12.39	0.96 (0.00)	0.10 (0.16)	0.94 (0.00)
Propulsive loading rate (N.s^{-1})	24.01 ± 11.41	24.37 ± 12.08	27.59 ± 11.62†	31.46 ± 13.25	31.93 ± 14.83	35.11 ± 12.28†	**0.01** (0.25)	**<0.001** (0.71)	0.99 (0.00)
Spring mass characteristics									
Vertical stiffness (kN.m^{-1})	30.53 ± 44.64	31.50 ± 36.29	30.78 ± 37.80	34.76 ± 45.61	35.53 ± 43.39	35.16 ± 41.60	0.36 (0.06)	**<0.001** (0.84)	0.74 (0.02)
Leg stiffness (kN.m^{-1})	15.21 ± 21.55	15.45 ± 17.70	15.01 ± 20.68	15.76 ± 24.48	15.56 ± 21.65	15.51 ± 21.79	0.39 (0.06)	0.14 (0.13)	0.15 (0.12)

Values are mean ± SD. C, S, and I respectively refer to ANOVA main effects of condition, speed and interaction between these two factors with P-value and partial eta-squared (η^2) in parentheses. Bold values indicate statistically significant findings.

**Significant different from CON ($P \leq 0.05$); †Significant different from EVA ($P \leq 0.05$).*

TABLE 3 | Changes in rating of perceived exertion (RPE) and comfort parameters for shoe only (CON), shoe with Ethyl-Vinyl Acetate orthotic (EVA), and shoe with Thermoplastic Poly-Urethane orthotic (TPU) conditions at low and high speeds.

Parameters	Low speed			High speed			ANOVA *P*-value (η^2)		
	CON	EVA	TPU	CON	EVA	TPU	C	S	I
RPE	10.4 ± 2.3	10.9 ± 2.6	10.6 ± 2.1	12.7 ± 3.1	13.2 ± 3.1	13.0 ± 3.0	0.14 (0.12)	**<0.001** (0.77)	0.84 (0.01)
Overall comfort	82.5 ± 31.3	93.9 ± 24.4	99.3 ± 24.3	86.0 ± 32.5	93.1 ± 30.6	97.1 ± 25.2	0.21 (0.09)	0.94 (0.00)	0.52 (0.03)
Heel cushioning	82.8 ± 29.9	94.7 ± 24.2	92.5 ± 26.7	82.6 ± 33.3	96.5 ± 22.6	88.6 ± 25.3	0.18 (0.10)	0.68 (0.01)	0.57 (0.03)
Forefoot cushioning	89.8 ± 35.9	96.8 ± 30.9	103.2 ± 23.2	88.2 ± 34.1	96.1 ± 27.9	102.4 ± 23.5	0.30 (0.07)	0.45 (0.04)	0.98 (0.00)
Medio-lateral control	84.4 ± 26.4	100.8 ± 23.9	99.8 ± 25.0	83.1 ± 32.5	97.9 ± 26.4	100.5 ± 25.1	0.06 (0.16)	0.58 (0.02)	0.74 (0.02)
Arch height	77.5 ± 33.0	98.2 ± 32.8	94.3 ± 24.6	74.2 ± 36.1	91.6 ± 33.0	96.4 ± 23.9	0.06 (0.19)	0.13 (0.14)	0.08 (0.16)
Heel cup fit	86.3 ± 27.8	98.8 ± 23.5	87.0 ± 27.5	86.2 ± 28.8	95.3 ± 22.8	88.3 ± 29.1	0.22 (0.09)	0.68 (0.01)	0.50 (0.04)

RPE was assessed using a 6–20 Borg scale and other comfort parameters were measures using a Visual Analog Scale (0–150 mm); Values are mean ± SD. C, S, and I respectively refer to ANOVA main effects of condition, speed and interaction between these two factors with P-value and partial eta-squared (η^2) in parentheses. Bold values indicate statistically significant findings.

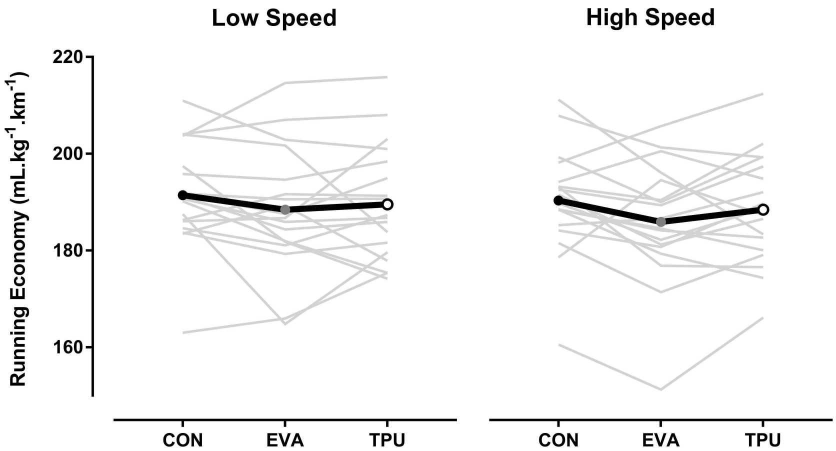

FIGURE 2 | Running Economy (RE) in three different footwear conditions (CON = Shoes only; EVA = Shoes + EVA orthotic; TPU = Shoes + TPU orthotic) over two speeds ("High Speed"= speed at ventilatory threshold and "Low Speed" = 15% below high speed). Note that there was no statistical significance ($P = 0.11$).

Increased RE corresponded with a reduction up to 4% in HR either while wearing EVA or TPU, at both speeds compared to CON. This result underscores the findings by Kelly et al. (2011), who found a 3% reduction in HR when using CFO made of EVA compared to running in shoes only at a submaximal speed of 10% above the first ventilatory threshold, suggesting CFO may reduce cardiorespiratory load imposed on the runner. However, decreased HR may probably be seen as a consequence rather than a cause of better RE (Barnes and Kilding, 2015).

Running Mechanics

All examined mechanical variables (except braking loading rate and leg stiffness), for all conditions, changed significantly from LS to HS. Our findings when running at LS and HS (∼55 and ∼70% of maximal running speed, respectively) are in line with Brughelli et al. (2011) who reported both higher vertical and horizontal forces and shorter contact times with increasing running speeds up to ∼65% of maximal velocity.

TPU reduced both mean and peak vertical loading rate by ∼12% at both speeds compared to CON and EVA. A lower vertical loading rate and vertical impact force of about ∼10% were the only biomechanical differences found between an injured and non-injured group of runners running at ∼14 km.h^{-1} (Hreljac et al., 2000). Reductions in vertical loading rate and peak vertical impact forces are suggested to decrease risk of running related injuries (Malisoux et al., 2018). Compared to EVA, TPU used in this study is a softer material dampening initial heel contact. This dampening effect could possibly explain our observations of reductions in peak vertical force and vertical rate of loading.

Another novel aspect is the reporting of horizontal force production as a mechanical variable influenced by different CFO materials. Compared to CON, EVA decreased peak braking forces by ∼4% (∼0.50 BW) and ∼3% (∼0.59 BW) and braking impulse by ∼3 and ∼2% for LS and HS, respectively. For the TPU condition, braking impulse also decreased at HS by ∼2% when compared to CON. In contrast, TPU in reference to both CON and EVA produced slightly higher peak braking forces of ∼6 and ∼3% for LS and HS, respectively. Peak braking forces (∼0.27 BW) were identified as the main risk factor for running related injuries in female runners running at moderate intensity of ∼9 km.h^{-1} (Napier et al., 2018). Both CFO used

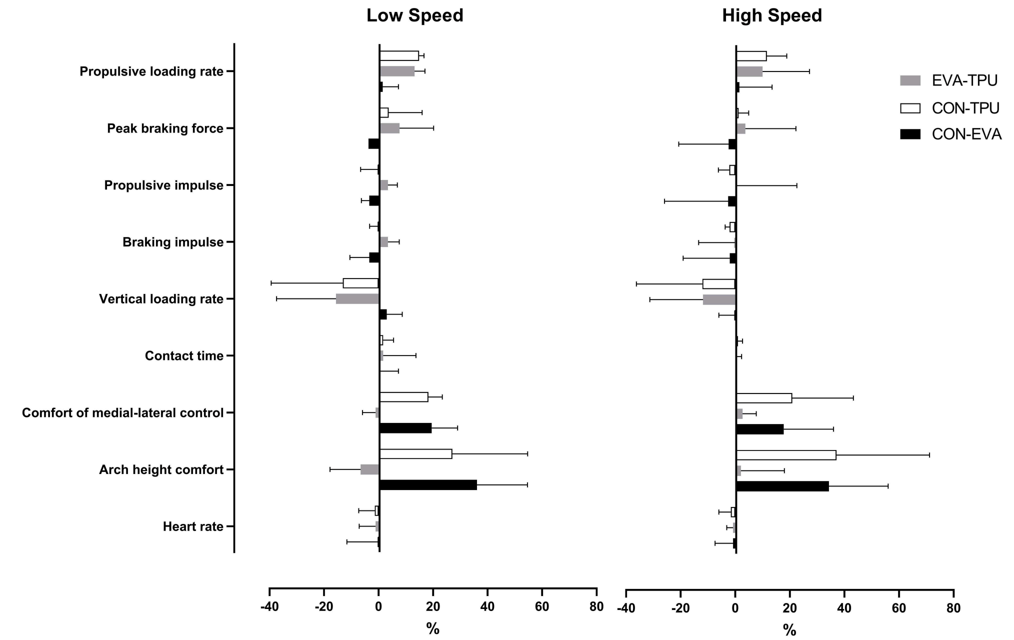

FIGURE 3 | An overview of percentage change for selected mechanical, physiological and comfort parameters when comparing three different conditions (CON-EVA= Shoes only vs. Shoes + EVA orthotic; EVA-TPU = Shoes + EVA orthotic vs. Shoes + TPU orthotic; CON-TPU = Shoes only vs. Shoes + TPU orthotic) over two speeds ("High Speed" = speed at ventilatory threshold and "Low Speed" = 15% below high speed).

in this study had an increased thickness of 8 mm of the heel and forefoot region. The combination of an increased thickness with increased cushioning for TPU possibly facilitates a rearfoot strike pattern during running and is known to increase braking forces (Lieberman et al., 2010). Our findings of acute reduced peak braking forces with EVA are an important observation that might be linked to the reduction of running related injuries. With regard to RE, a reduction of braking impulse will directly result in reduced amount of speed lost during running potentially resulting in a more economical running style (Nummela et al., 2007).

The magnitude of horizontal peak propulsive force was ∼4% higher for CON when compared to both EVA and TPU at both HS and LS. However, TPU significantly increased the duration of propulsion by ∼2% compared to CON. Also, TPU demonstrated ∼18% higher propulsive loading rate values across tested speeds compared to EVA and CON. Worobets et al. (2014) suggested that the limited loss of energy after a loading cycle with TPU could increase resilience and thus improve propulsion. Furthermore, lower vertical impact force, peak medial–lateral force and peak braking force and higher peak propulsive force are typical characteristics of an improved RE (Moore, 2016). Different mechanisms are at play, depending on the materials used for CFO. Where EVA might positively influence RE by reducing the magnitude of braking forces, a longer propulsion duration and increased rate of propulsive force could be a key kinetic modification induced by wearing TPU.

Contact times were slightly longer (1–2%) and associated with slightly decreased step frequency ∼1% for both orthotic conditions compared to CON. These observations can also possibly be explained by the effect of increased cushioning with CFO as seen in studies comparing minimalist and traditional footwear (Lohman et al., 2011). In our study, the magnitude of change in spatiotemporal characteristics was probably too narrow to induce measurable changes in RE between conditions.

Comfort

A trend toward significant improvement of comfort for medio-lateral control (∼20%) and arch height (∼25%) was found when both EVA and TPU were compared to CON at both speeds. These findings are in line with Burke and Papuga (2012) who reported improved medial-lateral control comfort together with overall comfort, heel cushioning and heel cup fit to correlate with improved RE. Over all measured comfort items, EVA and TPU improved comfort by ∼15% for both speeds compared to CON. Molded CFO generally increase comfort that induces functionally relevant changes in running mechanics such as decreased peak vertical force and vertical loading rate (Mundermann et al., 2003b).

Additional Considerations and Limitations

Because running mechanics may slightly differ between genders and the ground type surfaces, the findings of this study are only valid in the context of male recreational athletes running on a treadmill (Moore, 2016).

Additional mass of footwear is known to have a detrimental influence on RE. For every added 100 g per shoe, the energetic cost of running typically increases by ∼1% (Frederick, 1984). In this study, we decided not to match the mass for each shoe/orthotic footwear condition, and by doing so, keeping the interventions clinically relevant by increasing the external validity. The results of this study have shown RE to improve with the different CFO, despite the increased weight of both interventions. TPU and EVA were 14 and 8% heavier compared to CON, respectively. To eliminate the confounding effects of added shoe mass on the energetic cost and running mechanics, future studies should also look to match shoe mass of all conditions to isolate the "true" biomechanical and physiological effects of these two types of CFO.

The approach used in this study to determine the running speeds based on the individual ventilatory threshold determination is a strong methodological point. However, despite this precaution, highly inter-individual responses occurred. An inter-individual variability of 12.5 and 13.3% (CON), 12.4 and 14.0% (EVA) and 13.7 and 13.8% (TPU) was found for RE at LS and HS, respectively. These values were not lower than previously reported for running at set speeds (e.g., 10, 12, 14 km.h^{-1}) (Burke and Papuga, 2012). Inter-individual differences, often due to other modifiable and non-modifiable factors (e.g., anthropometrical, biomechanical, physiological, training) may have confounded the findings of this study.

Amount of individualization of the shape of the orthoses in this study was consistent for all participants and no corrective posting was applied. Controlling kinetic and kinematic responses (dose-response) across a group of participants hasn't been investigated previously (Griffiths and Spooner, 2018; Hoogkamer et al., 2018). Our results, with large inter-individual variability, highlight the fact that a "one-fits-all approach" must not be taken when interpreting mechanical and metabolic results. Individual responses, as plotted in **Figure 2**, highlight the between-subjects variability in RE on a controlled but standardized intervention.

CONCLUSION

RE marginally improved (albeit not significantly) when running at two different speeds, while wearing EVA custom foot orthoses compared to CON. The effect of TPU on RE was considered negligible. Comfort improved in the same conditions, while wearing either EVA or TPU in reference to CON, with larger effects for TPU. The footwear condition including EVA reduced braking forces and braking impulse occurring roughly in the first 25% of contact time, whereas TPU was associated with a decreased vertical loading rate and increased rate of force production during the propulsive phase. Male recreational athletes returning to competition can keep wearing their EVA orthoses.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

All subjects gave written informed consent in accordance with the Declaration of Helsinki and this study was carried out with the recommendations and approval of the Anti-Doping Laboratory Ethics Committee in Qatar (IRB Application Number 2017000201).

AUTHOR CONTRIBUTIONS

KV and OG contributed conception, design of the study, and collected all data. JR analyzed, datamined, and organized the kinematic database. KV performed the statistical analysis and wrote the first draft of the manuscript. All authors wrote sections of the manuscript and contributed to manuscript revision, read, and approved the submitted version.

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Fighting Doping in Elite Sports: Blood for All Tests!

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In the fight against doping, detection of doping substances in biological matrices is paramount. Analytical possibilities have evolved and sanctioning a doping scenario by detecting forbidden bioactive compounds circulating unmodified in blood is nowadays very attractive. In addition, the World Anti-Doping Agency (WADA) introduced the Athlete Biological Passport (ABP) a decade ago as a new paradigm inferring the use of prohibited substances or methods through longitudinal profiling, or serial analyses of indirect biomarkers of doping, to be both scientifically and legally robust. After the introduction in 2008 of an hematological module (i.e., based on variations of blood variables) aiming to identify enhancement of oxygen transport and any form of blood transfusion or manipulation, a urinary steroidal module was additionally introduced in 2014 composed of concentrations and ratios of various endogenously produced steroidal hormones. Some evidence tends to discredit steroid profiles obtained from urine analyses to detect the use of endogenous androgenic anabolic steroids (EAAS), when administered exogenously, due to high rates of false negatives with short half-life and topical formulations rendering profile alteration only minimal or equivocal. On the other hand, steroid hormones quantification in blood showed a promising ability to detect testosterone doping and interesting complementarities to the ABP thanks to the most recent analytical techniques (UHPLC-HRMS or/and MS/MS). This perspective article explores the opportunities of blood samples to monitor not only hematological but also steroid profiles in elite athletes.

Keywords: doping, steroids, testing, urine, serum, hematological passport

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The definition of doping in sport may be subject to several interpretation. According to the World Anti-Doping Code (WADA, 2018a), antidoping provisions may be considered violated when an athlete uses or attempts to use a prohibited substance or method or when a prohibited substance is detected in the urine or blood. The technical ability of an antidoping laboratory to detect such substance is hence key and nowadays warranted by strict international standards for laboratories and operating guidelines. While testosterone was isolated in 1927 and synthetically produced in 1935 (Kremenik et al., 2006), anabolic androgenic steroids (AASs) were only banned by the International Olympic Committee (IOC) and international sporting federations in 1974 (Gosetti et al., 2013) with a widespread screening of AAS since the 1976 Montreal Summer Olympics (275 drug tests with 12 gas chromatographs capable of screening over 200 banned substances) (Dugal et al., 1980; Kremenik et al., 2007). Urine and later blood collections have increased over time to reach the 322,050 samples analyzed in 2017. This large number is often put in perspective with the 2% rate of official adverse or atypical results in the tests performed in laboratories accredited by the World Anti-Doping Agency (WADA) (WADA, 2018b). This rate shall however be interpreted with care for several reasons. First, some tests may preventively deter doping simply by indicating to the athletes that they may be tested at any time. Second, because drug tests give priority to specificity rather than sensitivity: false-negative results underestimate true doping prevalence because of a lack of sensitivity (Kremenik et al., 2006). In an ideal scenario, laboratories would prospectively define and publicize standard testing procedures for all kind of substances, including unambiguous criteria for concluding positivity, and have the procedures validated in blinded experiments beforehand. Such experiments would define the substance, its dose, methods of delivery, timing of use relative to testing, and variations due to individual differences in metabolism (Berry, 2008). However, antidoping is a forensic science, not a medical one. When screening any sample for putative banned substances, the freedom to set sensitivity and specificity to an appropriate level is restricted in an antidoping context (Sottas et al., 2008a).

In parallel, blood samples are widely collected with more than 125,000 analyses in 2017 conducted mostly in serum or plasma (WADA, 2018b) for erythropoiesis stimulating agents (ESAs), growth hormone (GH), or growth hormone releasing factors (GHRFs). Since the first blood tests carried out at the 1994 Lillehammer Winter Olympic Games, blood analyses became widespread before major cycling events in 1997 (Robinson et al., 2005). The introduction of the hematological module of the ABP and its recognized potential (Robinson et al., 2011; Sottas et al., 2011; Schumacher et al., 2012) have consistently helped to make blood sampling more common and more widely accepted by athletes. A widely held view by antidoping scientists is that blood represents a much better human fluid than urine to establish the dose/effect response of a substance and to get a better biological signature of doping (Saugy et al., 2009).

Since several rapid methods to simultaneously detect numerous doping substances exist (Saugy et al., 2000; Ahrens et al., 2012), urine samples are still preferred to blood not only due to less invasive sampling but also because a slower metabolic rate in urine render their concentration of AASs and metabolites higher (or detectable) there at a given timepoint (Gosetti et al., 2013). Finding an exogenous forbidden substance in an athlete's urine sample may represent the simplest way to lead to a rule violation and sanction. However, doping practices have now evolved to circumvent shortened detection windows in conjunction with the exogenous application of micro-doses of substances already present in the body (e.g., testosterone). In response, WADA introduced the Athlete Biological Passport (ABP) a decade ago as a new paradigm inferring the use of prohibited substances or methods through longitudinal profiling, or serial analyses of indirect biomarkers of doping, to be both scientifically and legally robust (Vernec, 2014). A first hematological module (i.e., based on variations of blood parameters) introduced in December 2008 aimed to identify enhancement of oxygen transport and any form of blood transfusion or manipulation (Sottas et al., 2011). With more than 700 sanctions linked to the ABP monitoring for the last 10 years, this indirect approach may be considered successful (WADA, 2018b). A urinary module was additionally introduced in 2014 to monitor various endogenously produced steroidal hormones (Saugy et al., 2014). The bases of a module were indeed already introduced in 2008 (Sottas et al., 2008b). For instance, this steroidal module measures the concentrations of several glucuroconjugated and free urinary compounds linked to testosterone (T) and its metabolism: T, epitestosterone (E), androsterone (A), etiocholanolone (Etio), 5α-Androstane-3α,17β-diol (5αAdiol) and 5β-Androstane-3α,17β-diol (5βAdiol) and the T/E, A/T, A/Etio, 5αAdiol/5βAdiol, and 5αAdiol/E (Kuuranne et al., 2014; WADA, 2018c). Currently, some evidence however tends to discredit steroid profiles obtained from urine analyses to detect the use of exogenous AAS (Ayotte, 2010). Several confounding factors may induce high rates of false negatives. First, ranges of reference values often only refer to male Caucasian subjects that may not be extrapolated to all athletes (especially females) (Van Renterghem et al., 2010). Second, with the use of topical or transdermal formulations of T, large inter-individual variability in several markers render profile alteration only minimal or equivocal (Kotronoulas et al., 2018). Notably, low dosages of doping substances result in very short detection windows (Sottas et al., 2008a). Furthermore, the menstrual cycle undeniably impacts the ratios followed in the ABP. Changes in the T/E ratio during the cycle (due to variable excretion rates of epitestosterone) were thus reported with a marked effect of hormonal contraceptives (Schulze et al., 2014). More interestingly the use of an emergency contraceptive could potentially lead to an atypical profile in the ABP software (Mullen et al., 2017). Then, exogenous factors such as urine contamination by microorganisms (de la Torre et al., 2001; Mazzarino et al., 2011) alcohol and tea consumption (Kuuranne et al., 2014) were also reported to complicate the interpretation of steroid profiles in urine. Overall, the current urinary steroid profile in the ABP is challenged because of important pharmacological (formulation type and administration route), technical (sample preparation) and biological (bacterial, and enzymatic alteration) issues (Mareck et al., 2008).

For example, **Figure 1** illustrates a clear benefit in terms of increased sensitivity (i.e., with a much lower limit of quantitation) for testosterone detection in serum vs. urine after the application of a testosterone transdermal patch. The concentration at which quantitative results can be reported with a high degree of confidence is thus much lower in blood vs. urine.

In the view of a better harmonization, WADA has enacted a technical document of sport specific analysis (WADA, 2019b) encouraging the collection of serum samples for the detection of GH use. It is thus of prime importance to highlight the good stability of the blood matrix when testing for hormones in an antidoping context. For instance, storage of serum and plasma samples at 4°C was shown to be suitable for most hormones up to 120 h (Evans et al., 2001). Similarly, in an antidoping context, insulin like growth factor-I and type III procollagen peptide were stable in serum or clotted blood samples stored at 4°C for 5 days (Holt et al., 2009). Further, in an older study, T and androstenedione were remarkably stable in plasma (with the limitation of the radioimmunoassay measurement method) (Wickings and Nieschlag, 1976). The interest of plasma samples is obvious when trying to tackle a doping scenario because doping substances are targeted unmodified in their bioactive milieu (i.e.,

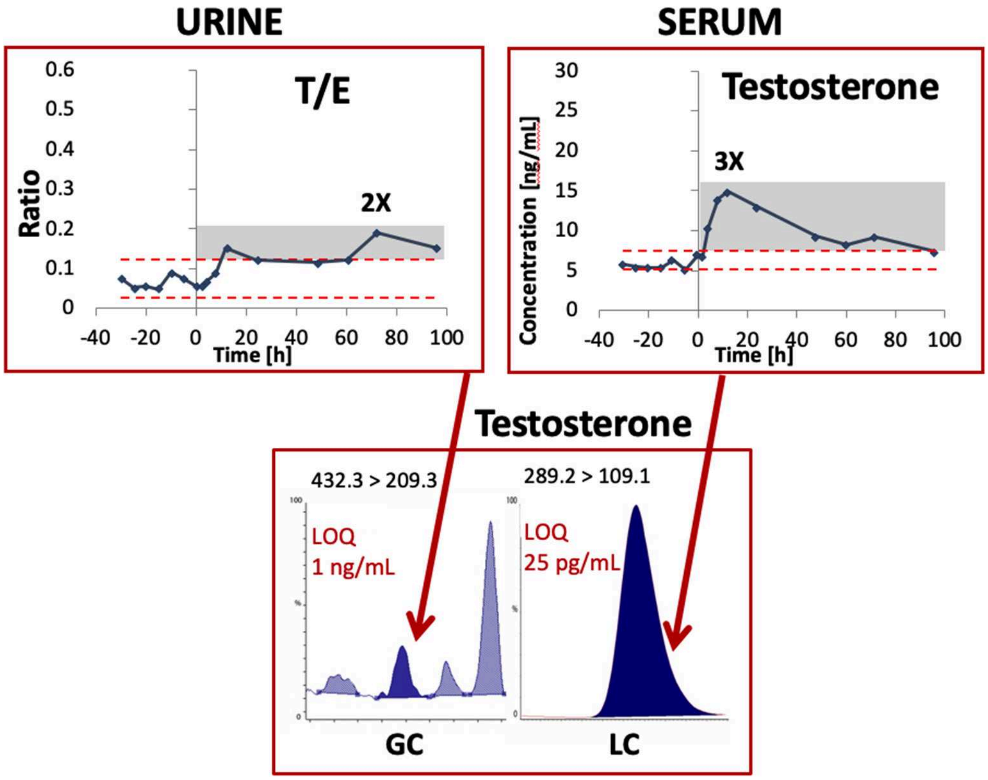

FIGURE 1 | Example of testosterone detection by mass spectrometry in an urine and serum sample from one single subject after the administration of a transdermal testosterone patch. Modified from Ponzetto et al. (2018) with permission. LOQ, limit of quantitation; T/E, Testosterone/Epitestosterone ratio.

closer to the exogenous application time), and samples are more difficult to falsify (Gosetti et al., 2013).

In terms of the chronological evolution of the main challenges and solutions in doping control analysis (Botre, 2008), state-of-the-art methods applied by accredited antidoping laboratories highlight future perspective for pertinent analyses on blood samples (Ponzetto et al., 2016). In a clinical context, medical diagnosis mostly rely on the analyses of blood samples also because of the availability of a laboratory with mass spectrometry analyses as gold standard for androgenic hormone screening (Handelsman and Wartofsky, 2013). For blood sample collected in an antidoping context (e.g., ABP samples), robust guidelines already exist to ensure limited time to analysis and sample stability (i.e., Blood Stability Score, BSS) (Robinson et al., 2016; WADA, 2019a). As a perspective to improve the ABP, the serial monitoring of steroid profiles in athletes trying to avoid AAS use detection (Alquraini and Auchus, 2018) could potentially be done from blood samples. In a recent study, an ultra-high performance liquid chromatography–high-resolution mass spectrometry (UHPLC-HRMS) method was developed for the quantification of 11 endogenous steroids in serum. In that study, concentration values measured by HRMS showed high correlation with the ones obtained by "traditional" tandem mass spectrometry (MS/MS) for all target hormones, with low absolute differences in the majority of cases suggesting that that HRMS could provide suitable performance for blood steroid analysis in the antidoping field (Ponzetto et al., 2018). In this context, "steroidomics" open the way to the untargeted simultaneous evaluation of a high number of compounds (Boccard et al., 2011). Such an approach could definitely open new antidoping perspectives for the screening of steroid metabolites after testosterone ingestion (Boccard et al., 2014) and is not limited to urinary samples. Indeed, the court of arbitration of sport has already taken a decision to sanction two female athletes because the "analysis of blood samples taken from both athletes established that such samples collected shortly before the Rio 2016 Olympic Games were found to contain an excessive concentration of testosterone" (TAS-CAS, 2019).

This decision in fact recognizes the utility of the blood analysis of steroids, because the biological interpretation of their concentration in blood, which may be affected by the intake of prohibited substances, is known to be more robust than in urine. From a legal point of view, there would be a clear advantage to use the same blood sample to "synchronize" the hematological and steroidal profiling. Repeated incentives have been formulated to improve the ABP in particular by including various information sources (Vernec, 2014) like performance data or external information from investigations.

Next-generation "omics," especially as applied to blood samples, have long been proposed as useful markers of doping (Reichel, 2011). For example, a very robust transcriptomic response (up to 3 weeks) after recombinant human erythropoietin administration was reported (Durussel et al., 2016). At the protein and metabolite level, recent research also used steroidomics to highlight novel biomarkers of testosterone doping in serum (Ponzetto et al., 2019). Further technological progress with current initiatives (Pitsiladis et al., 2016) is thought to lead to the development of robust biomarkers that are less prone to biological and technical bias, and valid in a court of law (Neuberger et al., 2011). Since current (blood and urine) samples can be stored for up to 10 years under the current WADA Code (WADA, 2018a), it may be very useful to collect more blood samples with the future discovery of new types of target compounds in mind.

One first step could indeed be to selectively analyze hematological and steroid profile from the same blood sample. Then, the numerous serum samples collected for GH detection (as per the compulsory discipline-specific analyses (TDSSA) by WADA (WADA, 2019b) could serve as a starting point to set reference values for steroid profiles in several population types. Interestingly, such reference values (for the hematological profiles) were recently published from blood samples collected in all athletes participating in two subsequent track & field events (International Association of Athletics Federations (IAAF) World Championships) (Robinson et al., 2019). Such an ideal scenario with samples collected in an athletic cohort is however challenging and costly to conduct but the need to utilize the ABP under such conditions my help facilitate the gathering of these samples and their subsequent analysis. Finally, the rapidly increasing analytical and data processing capabilities may also open avenues for a more widespread use of dried blood spots (DBS) samples in an antidoping context (Cox and Eichner, 2017). For instance, WADA as the main regulator of antidoping policies, strategically supports advances in antidoping with methodology that uses big data, and artificial intelligence for pattern recognition (Zaier, 2014), or initiatives to use machine learning techniques to enhance detection of substances (Maass, 2019).

In conclusion, despite the limitations inherent in the use of urinary steroidal profiling described here, there remains sufficient grounds to conduct the longitudinal profiling of steroids in blood due to the recent advances in mass spectrometry. The simultaneous profiling of the hematological and steroid modules in blood may help elucidate diverse molecular pathways, and allow a more complete investigation of the proteome and the metabolome. With the prospect of enhanced detection, antidoping organizations will be compelled to utilize the full scientific potential of methods to fully exploit the stored serum samples. Successful antidoping in the future predicates further advances in the detection of prohibited substances (or methods) in plasma and serum and these developments will inevitably pave the way for more blood to be drawn from athletes.

AUTHOR CONTRIBUTIONS

RF and MS drafted the manuscript. RF, JS, and MS contributed to revising the manuscript and expressed their approval of the final submitted version.

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Running Velocity Does Not Influence Lower Limb Mechanical Asymmetry

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We examined the effect of running velocity upon magnitude and range of asymmetry in the main kinetics and kinematics of treadmill running at constant, submaximal velocities. Nine well-trained, un-injured distance runners ran, in a random order, at seven running velocities (10, 12.5, 15, 17.5, 20, 22.5, and 25 km.h^{-1}) for 60 s (separated by > 90 s of rest) on an instrumented treadmill (ADAL3D-WR, Medical Development, France). Continuous measurement (1,000 Hz) of spatio-temporal, horizontal force production, and spring-mass characteristics was performed and data over 10 consecutive steps (5 right and 5 leg foot contacts after ∼50 s of running) were used for subsequent comparisons. Group mean and the range of asymmetry scores were assessed from the "symmetry angle" (SA) formulae where a score of 0%/100% indicates perfect symmetry/asymmetry. Mean SA scores for spatio-temporal variables were lower than 2%: contact time (0.6 ± 0.1%; range: 0.4–0.7%), aerial time (1.7 ± 0.2%; range: 1.3–2.1%) as well as step length and step frequency (0.7 ± 0.2%; range: 0.5–0.9%). Mean loading rate (5.3 ± 1.1%; range: 4.1–6.9%) and spring mass model [peak vertical force: 3.2 ± 1.6% (range: 2.9–3.4%); maximal downward vertical displacement: 11.2 ± 6.0% (range: 9.2–14.0%); leg compression: 3.6 ± 1.9% (range: 2.9–5.6%); vertical stiffness: 8.8 ± 1.9% (range: 7.1–11.6%); leg stiffness: 1.6 ± 0.6% (range: 1.2–2.9%)] presented larger mean SA values. Mean SA scores ranged 1–4% for duration of braking (1.3 ± 0.3%; range: 0.9–2.0%) and push-off (1.6 ± 0.9%; range: 1.2–2.4%) phases, peak braking (2.4 ± 1.1%; range: 1.6–3.6%), and push-off (1.7 ± 0.9%; range: 1.2–2.2%) forces as well as braking (3.7 ± 2.0%; range: 2.8–5.8%) and push-off (2.1 ± 0.8%; range: 1.3–2.6%) impulses. However, with the exception of braking impulse ($P = 0.005$), there was no influence of running velocity on asymmetry scores for any of the mechanical variables studied ($0.118<P<0.920$). Modifying treadmill belt velocity between 10 and 25 km.h^{-1} induced large adjustments in most running kinetics and kinematics. However, there was no noticeable difference in group mean and the range of asymmetry values across running velocities, with the magnitude of these scores being largely dependent on the biomechanical variable of interest. Finally, the relatively large range of asymmetry between participants for some variables reinforces the importance of assessing asymmetry on an individual basis.

Keywords: imbalance, symmetry angle scores, running velocity, kinetics, kinematics, spring-mass model

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INTRODUCTION

Completely symmetrical gait is not possible since having a dominant leg, for instance, is natural. Anecdotally, even the fastest sprinter officially recorded (Longman, 2017) may have an asymmetrical running gait, since he strikes the ground with apparently more force with his right leg than he does with his left (New York Times website). To date, a growing body of research focuses on between-leg similarities—i.e., typically measured using symmetry scores to examine their effects on athletic performance (Bishop et al., 2018). Subtle asymmetries are not always noticeable to the naked eye, even in expert athletic coaches, or necessarily kinesthetically apparent to an athlete. An advanced analysis of an individual's running pattern is therefore necessary to evaluate symmetry in biomechanical factors not readily detectable by a coach, such as ground reaction force variables.

Asymmetry occurs when there is any deviation from symmetry, i.e., the exact replication of one limb's movement by the other (Exell et al., 2012a). In the literature, comparisons of commonly used symmetry indices indicate that none is preferred, for instance, to examine the success of rehabilitation process (Błazkiewicz et al., 2014). That said, Bishop et al. (2016) argued that reporting asymmetries via the "Symmetry Angle" (SA) (Zifchock et al., 2008) method holds some advantages over other options (i.e., limb symmetry index, bilateral strength asymmetry, asymmetry index). The SA is a dimensionless measure of asymmetry that does not suffer from artificial inflation, unlike the symmetry index that requires a reference value (Exell et al., 2012a), and is therefore a robust measure of asymmetry that can be used across kinematic and kinetic variables (Carpes et al., 2010). Marked asymmetry in maximal plantar force (measured using an in-shoe pressure system), but not contact times, slightly increases with increasing treadmill velocity between 12 and 16 km.h^{-1} for athletes $<$ 9 months post anterior cruciate ligament reconstruction despite having completed functional return to sport criteria (Thomson et al., 2018). Whether the right and left legs typically apply equal ground forces (as measured directly) from a wider range of constant, slow-to-fast running velocities in apparently healthy runners remains unclear.

Monitoring for inter-limb discrepancies is becoming common practice using instrumented treadmills that allows a large sample of successive ground reaction force traces to be collected (Carpes et al., 2010). Vertical force parameters (and derived spring-mass variables) have been used to investigate potential asymmetries in stride mechanical pattern due to factors such as fatigue (Radzak et al., 2017), previous injury (Zifchock et al., 2006) or various running techniques (Karamanidis et al., 2003). Comparatively, asymmetry in braking, or propulsive (anteroposterior) forces and resulting impulses, which could be important with regard to limb differences in contributing to maintenance of forward momentum, have rarely been explored. In one study of non-injured team sport players, no significant differences were found for any kinetic/kinematic variables between right and left legs (Brughelli et al., 2010). Only one running velocity (corresponding ∼to 80% of maximum velocity of tested individuals) was explored, while any bilateral leg difference was not assessed using the recommended SA score (Exell et al., 2012a).

The main purpose of this study was to examine the effect of running velocity upon magnitude and range of asymmetry in the main kinetics and kinematics of treadmill running at constant, submaximal velocities.

METHODS

Participants

Nine well-trained middle-distance runners (mean ± SD age, 26.5 ± 4.8 years; stature, 1.77 ± 0.05 m; body mass, 66.4 ± 4.2 kg; recent 5 km time, 15:58± 0:57 min:s) were recruited for this study. All participants had a minimum of 3 years consistent running training at a competitive level. Training volume for the 6 weeks preceding testing was 6–11 hr.wk^{-1} running, and 1–2 hr.wk^{-1} cross-training which involved a mixture of plyometrics, light resistance exercise, and run specific functional movement training. Foot strike pattern was determined using sagittal plane video-analysis at a sampling frequency of 240 Hz using an iPhone 7 (Apple, California, US). In our sample of nine participants, five and four were rearfoot and midsole strikers at 10 km.h^{-1}, respectively. Participants had no known history of cardiovascular, neurological, or orthopedic problems, were injury free for the 3 months leading up to the data collection and gave written informed consent prior to participation in the study. Ethical approval for the study was provided by the Anti-Doping Laboratory Ethics Committee in Qatar (IRB Application Number: E2015000073) and was undertaken according to the principles outlined in the Declaration of Helsinki.

Experimental Procedures

Testing took place during the competitive outdoor in-season (November) as part of a training camp in Doha (State of Qatar). The main experimental session started with the completion of a standardized warm-up (5 min of running at 10 km.h^{-1}, followed by 1 min at 15 and 20 km.h^{-1} and 1–2 habituation runs of ∼20 s at 25 km.h^{-1}). After 5 min of passive rest, participants ran at seven running velocities (10, 12.5, 15, 17.5, 20, 22.5, and 25 km.h^{-1}) for 60 s with >90 s of rest (quiet standing upright) between efforts. Running velocities were assigned in a randomized and counterbalanced order among participants. They ran on an instrumented treadmill (ADAL3D-WR, Medical Development—HEF Tecmachine, France) in an indoor facility maintained at standard environmental conditions (∼24°C/45% of relative humidity). Participants commenced all rest-to-exercise transitions (or *vice-versa*) by holding the sidebars of the treadmill, while stepping directly on the moving treadmill belt during work intervals or on the sides of the treadmill during the recovery periods, respectively. They were asked to refrain from strenuous exercise, avoid caffeine and alcohol in the 24 h preceding the measurements, and to arrive at the testing sessions in a rested and hydrated state, at least 3 h postprandial. Participants confirmed that they were familiar with treadmill running and completed at least two training sessions on a treadmill in the year preceding the testing.

Running Mechanics

Data were continuously sampled at 1,000 Hz, and after appropriate filtering (Butterworth-type 30 Hz low-pass filter, fourth order), instantaneous data of vertical, net horizontal, and total (resultant) ground reaction forces were averaged over the support phase of each step (vertical force above 30 N), and expressed in body weight (N). These data were completed by measurements of the main step kinematic variables: contact time (s), aerial time (s), step frequency (Hz), and step length (m). Peak braking and peak propulsive forces (body weight or BW), duration of braking and push-off phases (s) along with braking and push-off impulses ($BW.s^{-1}$) were determined. Finally, vertical mean loading rate ($BW.s^{-1}$) was calculated as the mean value of the time-derivate of vertical force signal within the first 50 ms of the support phase (Giandolini et al., 2013).

A linear spring-mass model of running was used to investigate the main mechanical integrative parameters characterizing the lower limbs behavior during running. Vertical stiffness ($K_{vert} = Fz_{max}.\Delta z^{-1}$, $kN.m^{-1}$) was calculated as the ratio of peak vertical forces (Fz_{max} in N) to the maximal vertical downward displacement of center of mass (Δz in m), which was determined by double integration of vertical acceleration of center of mass over time during ground contact. Leg stiffness ($K_{leg} = Fz_{max}.\Delta L^{-1}$, in $kN.m^{-1}$) was calculated as the ratio of Fz_{max} to the maximum leg spring compression (ΔL) [$\Delta z + L_0 - \sqrt{(L_0{}^2 - (0.5 \times \text{running velocity} \times \text{contact time})^2)}$, in m], both occurring at mid-stance. Initial leg length (L_0, great trochanter to ground distance in a standing position, in m) was determined from participant's stature as $L_0 = 0.53 \times$ stature (Morin et al., 2005).

Symmetry Angle

For each participant, inter-leg symmetry was measured using the symmetry angle (SA) and rectified so that all values were positive (Exell et al., 2012b). The SA was calculated using the equation below (Zifchock et al., 2008).

Symmetry angle (SA) =

$$\frac{\left| 45^\circ - \left(tan^{-1}\left[\frac{left}{right}\right]\right)\right|}{90} \times 100$$

but if

$$\left(45^\circ - tan^{-1}\left[\frac{left}{right}\right]\right) > 90$$

then

$$\frac{\left| 45^\circ - \left(\tan^{-1}\left[\frac{left}{right}\right] - 180\right)\right|}{90} \times 100$$

The SA reports an absolute score (between 0 and 100%) that describes the deviation of the observed relationship between the two legs from a theoretically perfect relationship; where a score of 0% indicates perfect symmetry and 100% indicates perfect asymmetry.

Data Analysis and Statistics

Ten consecutive steps (5 right and 5 leg foot contacts) beginning at the 50th second of each 60-s running bout were analyzed, and the averaged values were calculated for further analysis. In the context of our study (running velocities up to 25 $km.h^{-1}$), this represents an optimal trade-off between enough time for gait to normalize for consistency of measurements and prevention of significant fatigue development that might otherwise influence running style. Participants were informed to "run normally" during the entire duration of each run, without knowing the exact moment of the sampling (Morin et al., 2009). Descriptive statistics are presented as mean values ± SD. Normal distribution of the data was checked by the Shapiro-Wilk normality test. Mechanical data were tested using a one factor (time) ANOVA for repeated measures (10, 12.5, 15, 17.5, 20, 22.5, and 25 $km.h^{-1}$). To assess assumptions of variance, Mauchly's test of sphericity was performed using all ANOVA results. A Greenhouse-Geisser correction was performed to adjust the degree of freedom if an assumption was violated, while a Bonferroni *post-hoc* multiple comparison was performed if a significant main effect was observed. For each ANOVA, partial eta-squared (η^2) was calculated as measures of effect size. Values of 0.01, 0.06, and above 0.14 were considered as small, medium and large, respectively. All statistical calculations were performed using SPSS statistical software V.24.0 (IBM Corp., Armonk, NY, USA). The significance level was set at $p < 0.05$.

RESULTS

Mean SA scores for spatio-temporal variables were lower than 2%: contact time (0.6 ± 0.1%; range: 0.4–0.7%), aerial time (1.7 ± 0.2%; range: 1.3–2.1%) as well as step length and step frequency (0.7 ± 0.2%; range: 0.5–0.9%; **Figure 1**). Mean loading rate (5.3 ± 1.1%; range: 4.1–6.9%) and spring mass model [peak vertical force: 3.2 ± 1.6% (range: 2.9–3.4%); maximal downward vertical displacement: 11.2 ± 6.0% (range: 9.2–14.0%); leg compression: 3.6 ± 1.9% (range: 2.9–5.6%); vertical stiffness: 8.8 ± 1.9% (range: 7.1–11.6%); leg stiffness: 1.6 ± 0.6% (range: 1.2–2.9%)] presented a trend of larger mean SA scores (**Figure 2**). Mean SA scores ranged 1–4% for duration of braking (1.3 ± 0.3%; range: 0.9–2.0%) and push-off (1.6 ± 0.9%; range: 1.2–2.4%) phases, peak braking (2.4 ± 1.1%; range: 1.6–3.6%), and push-off (1.7 ± 0.9%; range: 1.2–2.2%) forces as well as braking (3.7 ± 2.0%; range: 2.8–5.8%) and push-off (2.1 ± 0.8%; range: 1.3–2.6%) impulses (**Figure 3**). However, with the exception of braking impulse ($P = 0.005$; $\eta^2 = 0.31$), there was no influence of running velocity on mean SA scores for any of the mechanical variables studied ($0.118 < P < 0.920$; $0.01 < \eta^2 < 0.23$; **Figures 1–3**). Associations of SA scores between selected variables are displayed in **Table 1**.

When all values were pooled for the both legs, increasing treadmill velocity from 10 to 25 $km.h^{-1}$ induced shorter contact times (0.243 ± 0.033 vs. 0.141 ± 0.012 s; −41.2 ± 7.7%), longer aerial times (0.113 ± 0.017 vs. 0.140 ± 0.014 s; +25.6 ± 20.1%), faster step frequency (2.82 ± 0.23 vs. 3.59 ± 0.27 Hz; +27.2 ± 11.2%) along with longer step length (0.099 ± 0.071 vs. 0.195 ± 0.014 m; +98.0 ± 18.5%) (all $P < 0.05$; $\eta^2 > 0.62$; **Figure 4**;

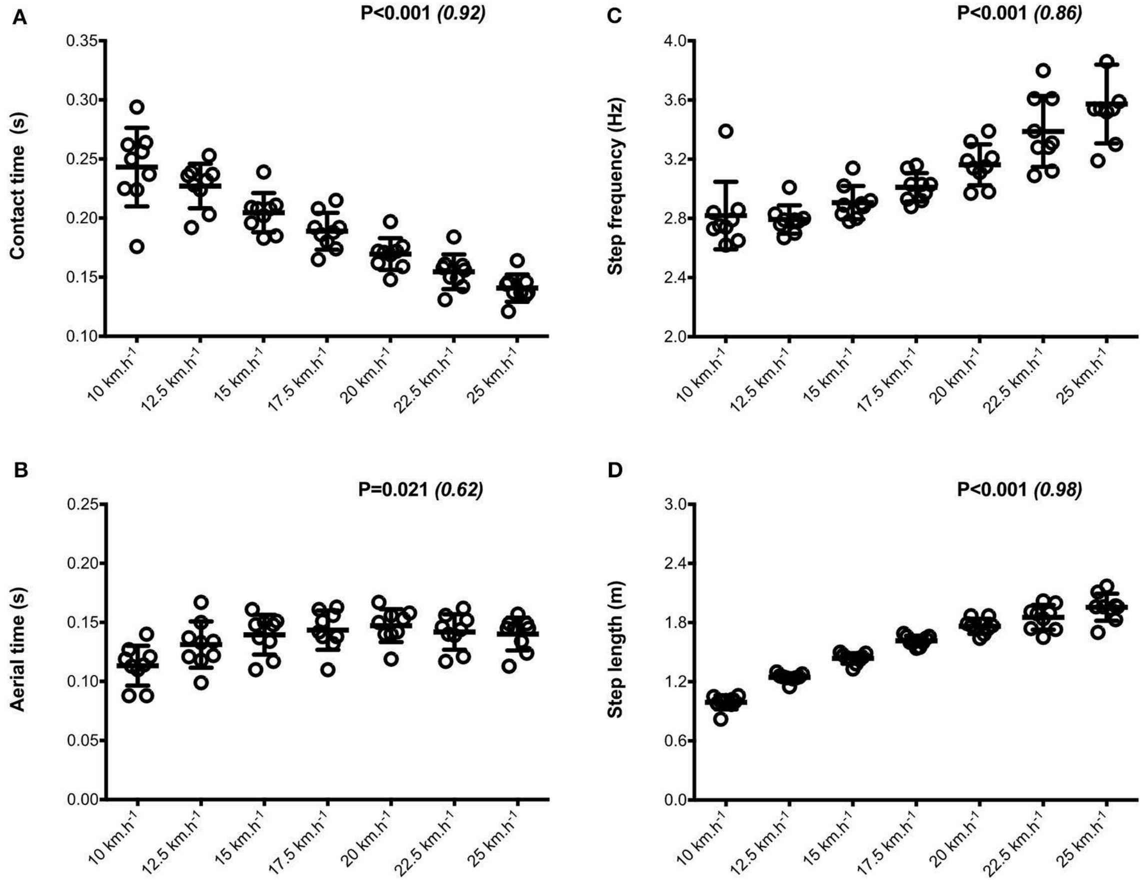

FIGURE 1 | Spatio-temporal parameters. Contact time **(A)**; aerial time **(B)**; step frequency **(C)**; step length **(D)**. Values are mean ± SD. *P*-value and partial eta-squared in parentheses for the ANOVA main effect of running velocity.

Table 2). Values for mean loading rate (39.2 ± 6.8 vs. 79.4 ± 22.7 BW.s^{-1}; +103.6 ± 45.0%) and vertical stiffness (40.6 ± 15.5 vs. 84.7 ± 13.9 kN.m^{-1}; +122.4 ± 44.9%) all nearly doubled (all $P < 0.001$; $\eta^2 > 0.74$), while changes in peak vertical force (1,679 ± 140 vs. 2,024 ± 159 N; +20.8 ± 7.7%), maximal downward vertical displacement (0.047 ± 0.016 vs. 0.026 ± 0.008 m; −43.0 ± 12.8%) and leg compression (0.083 ± 0.026 vs. 0.120 ± 0.026 m; +52.3 ± 46.9%) were more modest ($P < 0.05$; $\eta^2 > 0.70$) and leg stiffness (22.8 ± 10.4 vs. 17.5 ± 2.8 kN.m^{-1}; −16.2 ± 19.5%) remained unchanged ($P = 0.142$; $\eta^2 = 0.24$; **Figure 5**; **Table 3**). Duration of braking (0.124 ± 0.013 vs. 0.069 ± 0.010 s; −43.8 ± 4.9%) and push-off (0.130 ± 0.013 vs. 0.074 ± 0.010 s; −43.0 ± 5.1%) phases shortened, while peak braking (−0.51 ± 0.14 vs. −1.01 ± 0.18 BW; +105.5 ± 43.5%) and push-off (0.28 ± 0.03 vs. 0.84 ± 0.08 BW; +197.5 ± 35.7%) forces as well as braking (−16.2 ± 1.5 vs. −26.3 ± 3.1 BW.s^{-1}; +62.4 ± 17.3%) and push-off (16.6 ± 1.5 vs. 26.5 ± 3.1 BW.s^{-1}; +60.3 ± 20.2%) impulses increased ($P < 0.001$; $\eta^2 > 0.82$; **Figure 6**; **Table 4**).

DISCUSSION

The purpose of our study was to examine kinematic and kinetic asymmetries, with specific interest in how these asymmetries change with increasing running velocity in uninjured runners. Runners' SA scores were analyzed at seven different velocities (range: 10–25 km.h^{-1}) to determine whether a similar degree of asymmetry was present. Averaged SA values were small (< 4%) across most spatio-temporal and spring mass variables, while horizontal force measures displayed larger asymmetry. However, there was virtually no influence of running velocity on asymmetry scores for any of the mechanical variables studied since our data exhibited relatively unchanging average values, and consistently low-to-moderate asymmetry scores across all velocities. Overall, asymmetries in all key mechanical parameters did not differ significantly between slower and faster running velocities.

No Influence of Running Velocity on Asymmetry

Considerable evidence exists for natural kinetic asymmetries during both submaximal (Zifchock et al., 2008) and maximal velocity (Exell et al., 2012b) running. However, it is unclear whether or not the magnitude of these asymmetries changes with increasing velocity. Previously, imbalances in propulsion and maximal downward vertical displacement measures have been shown to increase with velocity (Belli et al., 1995), indicating a potential for greater asymmetry in running, while others found

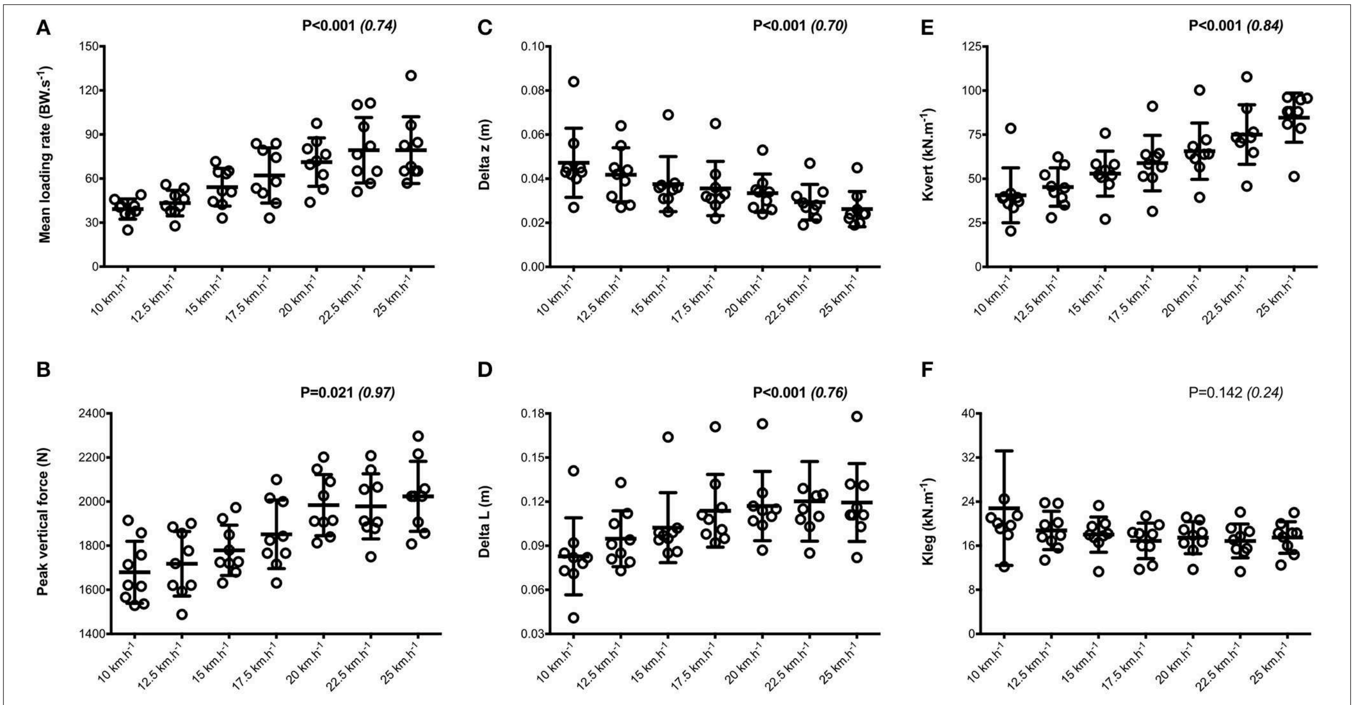

FIGURE 2 | Dynamics and spring-mass variables. Mean loading rate **(A)**; peak vertical force **(B)**; Delta z, center of mass vertical displacement **(C)**; Delta L, leg compression **(D)**; Kleg, leg stiffness **(E)**; Kvert, vertical stiffness **(F)**. Values are mean ± SD. *P*-value and partial eta-squared in parentheses for the ANOVA main effect of running velocity.

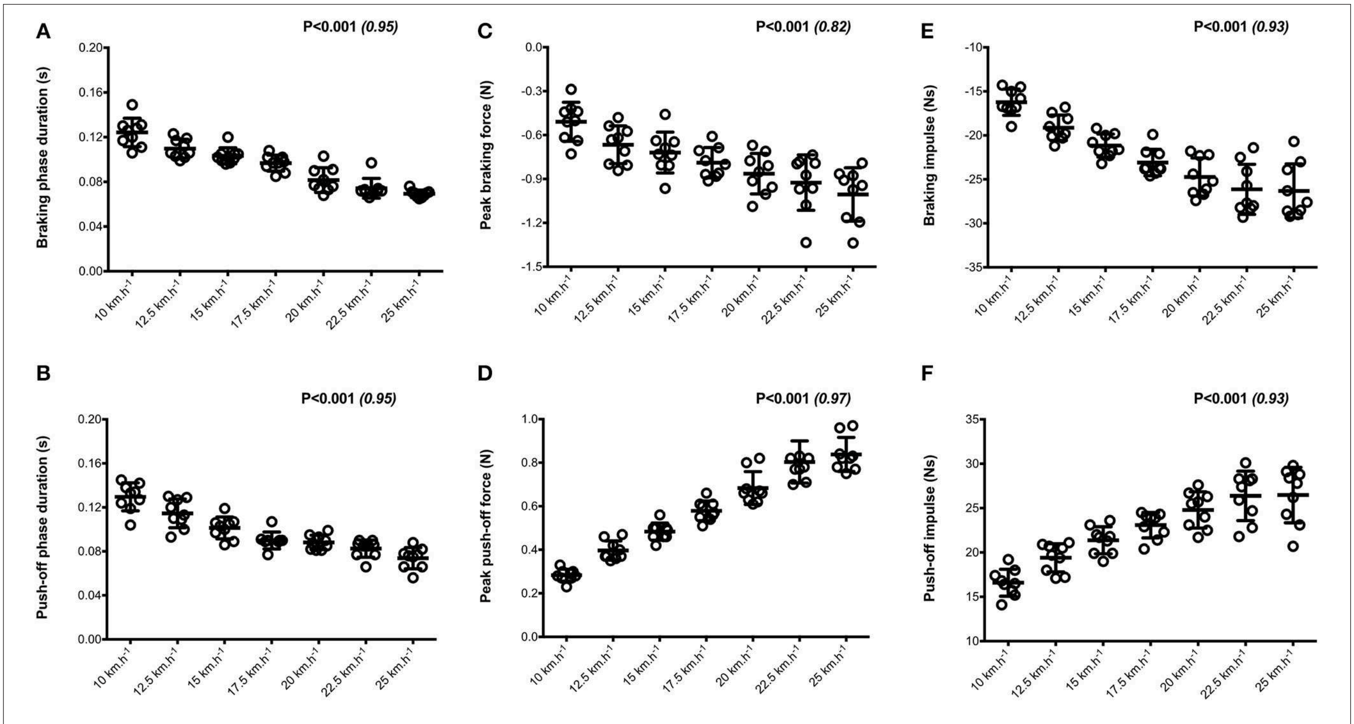

FIGURE 3 | Horizontal force production variables. Braking and push-off phases duration (**A,B**, respectively); Peak braking and push-off forces (**C,D**, respectively); Braking and push-off impulses (**E,F**, respectively). Values are mean ± SD. *P*-value and partial eta-squared in parentheses for the ANOVA main effect of running velocity.

TABLE 1 | Relationships between symmetry angle scores of selected running mechanical variables (all running speeds combined; $n = 9$).

	Contact time	Aerial time	Step frequency	Step length	Mean loading rate	Peak vertical force	Maximal downward vertical displacement	Leg compression	Vertical stiffness	Leg stiffness	Braking phase duration	Peak braking force	Braking impulse	Push–off phase duration	Peak push–off force	Push–off impulse
Contact time	1	−0.092	−0.106	−0.106	0.189	−0.238	−0.147	−0.219	−0.124	0.240	0.086	−0.203	−0.226	**0.523****	−0.156	0.194
Aerial time		1	**0.858****	**0.858****	0.003	0.247	**0.471****	0.116	**0.521****	−0.210	0.078	**−0.267***	**0.349****	0.083	**0.269***	−0.060
Step frequency			1	**1.000****	−0.038	0.110	**0.351****	0.115	**0.415****	**−0.264***	0.166	−0.135	**0.437****	0.010	**0.389****	−0.039
Step length				1	−0.038	0.110	**0.351****	0.115	**0.415****	**−0.264***	0.166	−0.135	**0.437****	0.010	**0.389****	−0.039
Mean loading rate					1	−0.152	−0.117	−0.222	−0.069	−0.007	0.079	**−0.274***	−0.090	0.133	−0.052	**−0.367****
Peak vertical forces						1	**0.804****	**0.624****	**0.667****	0.204	−0.023	−0.045	0.139	−0.137	0.121	0.168
Maximal downward vertical displacement							1	**0.651****	**0.975****	0.123	−0.130	−0.164	0.118	−0.083	**0.274***	0.235
Leg compression								1	**0.594****	**0.417****	0.023	0.058	**0.328****	−0.215	0.185	0.248
Vertical stiffness									1	0.092	−0.141	−0.206	0.096	−0.047	**0.304***	0.205
Leg stiffness										1	0.162	−0.016	−0.083	**0.276***	−0.166	**0.285***
Braking phase duration											1	0.197	**0.387****	**0.481****	−0.108	−0.047
Peak braking force												1	**0.413****	−0.132	−0.064	0.214
Braking impulse													1	−0.075	0.180	−0.037
Push–off duration														1	−0.135	0.189
Peak push–off force															1	0.248
Push–off impulse																1

Significant ANOVA P-values are represented in bold.
$^{*}P < 0.05$ and $^{**}P < 0.01$ for significant relationships.

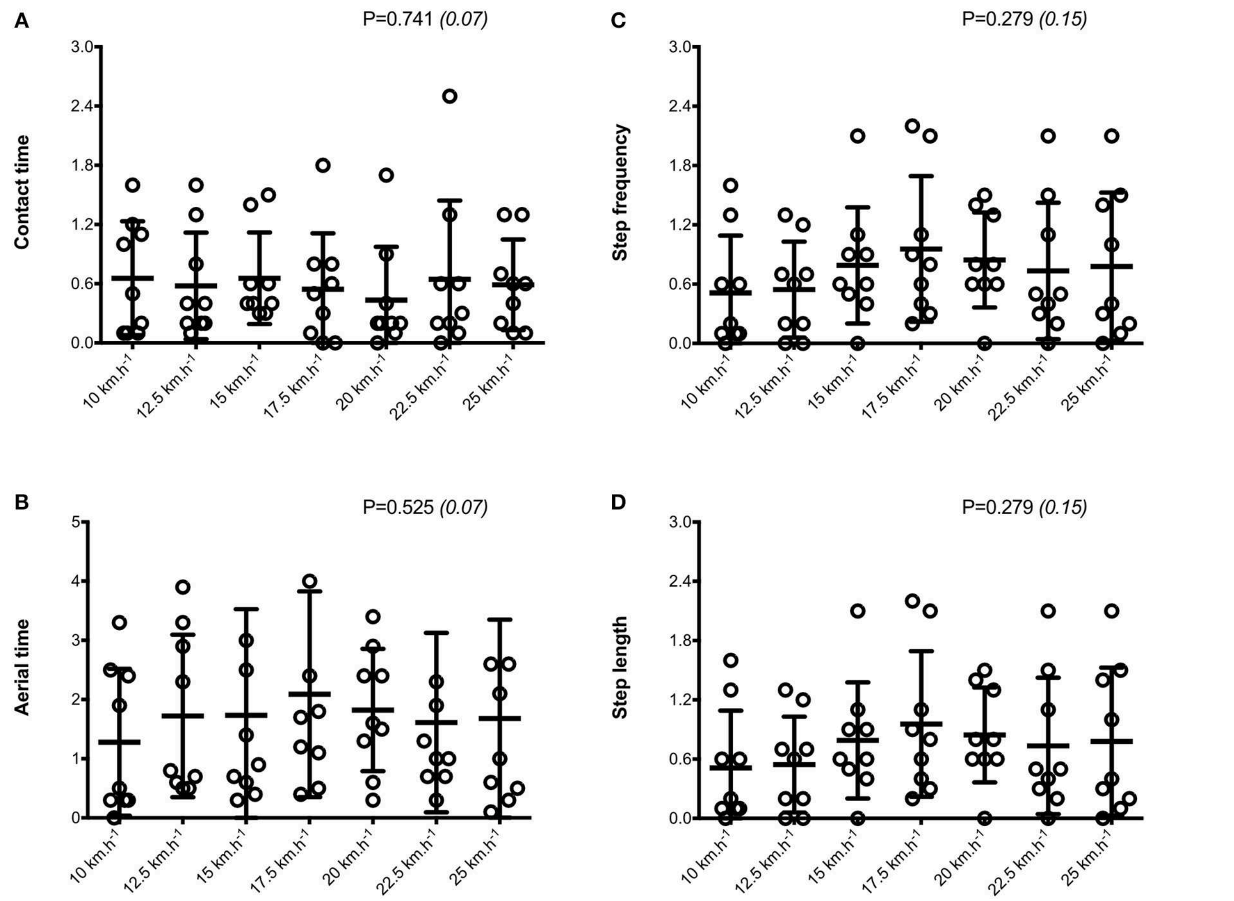

FIGURE 4 | Symmetry angle scores (expressed as %) for spatio-temporal parameters. Contact time **(A)**; aerial time **(B)**; step frequency **(C)**; step length **(D)**. Values are mean ± SD. *P*-value and partial eta-squared in parentheses for the ANOVA main effect of running velocity.

TABLE 2 | Relative changes for spatio–temporal parameters between 10 and 25 km.h^{-1} (n = 9).

Variables (% change in reference to 10 km.h^{-1})	12.5 km.h^{-1}	15 km.h^{-1}	17.5 km.h^{-1}	20 km.h^{-1}	22.5 km.h^{-1}	25 km.h^{-1}	*P*-value (Effect size)
Contact time	−4.9 ± 16.0	−14.6 ± 13.0^{ab}	−21.2 ± 10.8^{ab}	−29.3 ± 10.1^{ab}	−35.8 ± 6.8^{ab}	−41.2 ± 7.7^{ab}	<0.001 (0.92)
Aerial time	16.4 ± 13.3	23.9 ± 8.3^{a}	27.3 ± 10.8^{a}	31.3 ± 14.4^{a}	26.8 ± 17.5^{a}	25.6 ± 20.1^{a}	<0.001 (0.62)
Step frequency	−0.5 ± 6.8	3.6 ± 7.6^{b}	7.3 ± 7.2^{b}	12.6 ± 7.9^{ab}	20.3 ± 5.8^{ab}	27.2 ± 11.2^{a}	<0.001 (0.86)
Step length	26.1 ± 9.9^{a}	45.6 ± 12.3^{ab}	63.7 ± 12.6^{ab}	78.5 ± 14.0^{ab}	87.3 ± 8.9^{a}	98.0 ± 18.5^{a}	<0.001 (0.98)

Values are mean ± SD.
[a] *Significantly different from 10 km.h^{-1} (P < 0.05).*
[b] *Significantly different from the previous running velocity (P < 0.05).*

that an increase in running velocity does not fundamentally alter kinetic and kinematic symmetry (Karamanidis et al., 2003; Zifchock et al., 2006). In our study, with the exception of one variable (i.e., faster velocities had less asymmetry for braking impulse), we found no differences in SA scores across a range of slow and fast running velocities for >15 gait variables in non-injured, well trained runners. Even for spatiotemporal parameters, for which the average values change drastically, the level of asymmetry was consistently small across all velocities. Tested runners were also symmetrical for the ground reaction force variables measured, with minimal differences across a range of low-to-fast running velocities. The main observation of our study is that left and right asymmetry values of running kinetics and kinematics didn't increase as velocity varied between 10 and 25 km.h^{-1}.

Comparison of Asymmetry Between Variables

Although the important temporal variables of step frequency, step length, and contact time showed low asymmetry, SA scores

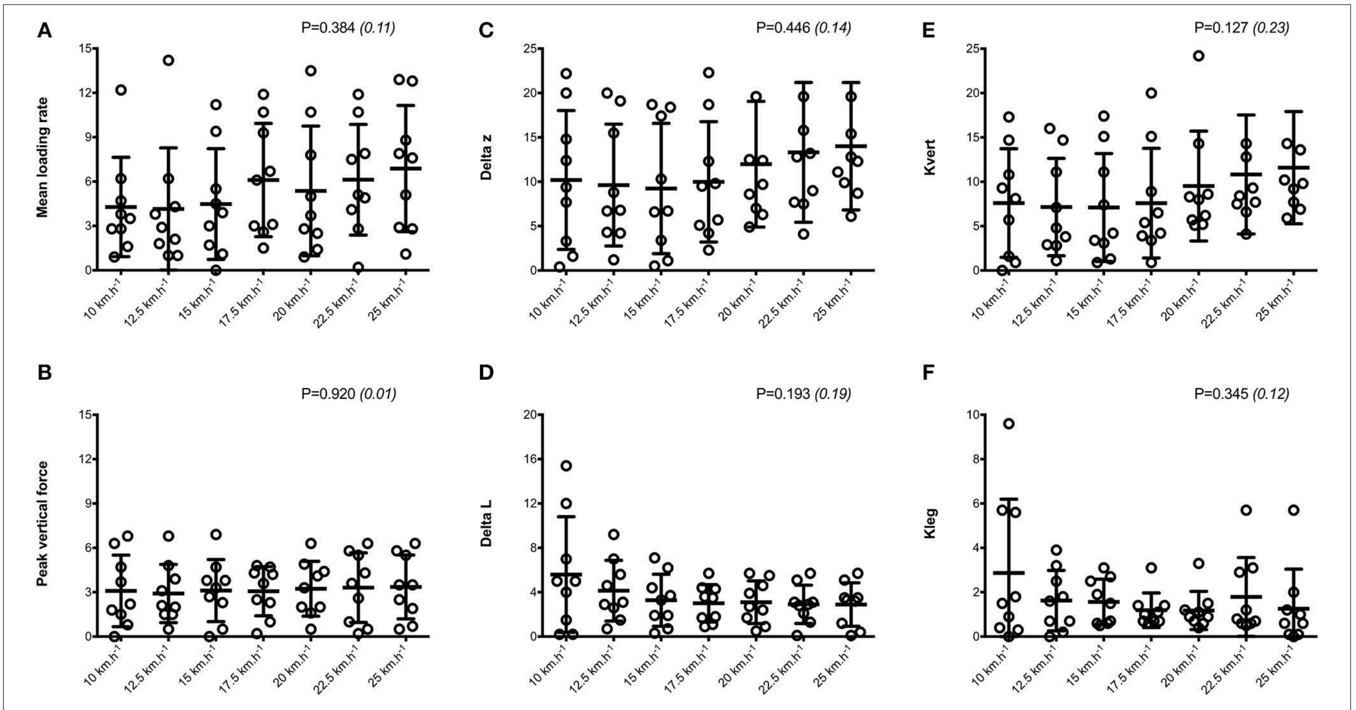

FIGURE 5 | Symmetry angle scores (expressed as %) for dynamics and spring-mass variables. Mean loading rate **(A)**; peak vertical force **(B)**; Delta z, center of mass vertical displacement **(C)**; Delta L, leg compression **(D)**; Kleg, leg stiffness **(E)**; Kvert, vertical stiffness **(F)**. Values are mean ± SD. *P*-value and partial eta-squared in parentheses for the ANOVA main effect of running velocity.

TABLE 3 | Relative changes for dynamics and spring–mass variables between 10 and 25 km.h^{-1} ($n = 9$).

Variables (% change in reference to 10 km.h^{-1})	12.5 km.h^{-1}	15 km.h^{-1}	17.5 km.h^{-1}	20 km.h^{-1}	22.5 km.h^{-1}	25 km.h^{-1}	*P*-value (Effect size)
Mean loading rate	10.2 ± 14.3	37.0 ± 15.0^{ab}	57.4 ± 35.4^{a}	81.0 ± 22.1^{a}	101.3 ± 36.2^{a}	103.6 ± 45.0^{a}	**<0.001 (0.74)**
Peak vertical forces	2.7 ± 9.2	6.3 ± 7.6	10.5 ± 7.8	18.5 ± 8.2^{ab}	18.4 ± 11.1^{a}	20.8 ± 7.7^{a}	**0.021 (0.97)**
Maximal downward vertical displacement	−9.0 ± 21.2	−20.1 ± 7.4^{a}	−25.0 ± 4.9^{a}	−27.6 ± 9.5^{a}	−37.3 ± 7.1^{ab}	−43.0 ± 12.8^{a}	**<0.001 (0.70)**
Leg compression	22.0 ± 41.2	30.0 ± 38.0^{a}	43.9 ± 37.5^{a}	49.5 ± 43.9^{a}	52.0 ± 39.4^{a}	52.3 ± 46.9^{a}	**<0.001 (0.76)**
Vertical stiffness	18.3 ± 28.9	34.6 ± 17.6^{a}	48.7 ± 13.5^{a}	67.6 ± 22.2^{a}	92.7 ± 27.7^{ab}	122.4 ± 44.9^{a}	**<0.001 (0.84)**
Leg stiffness	−9.5 ± 23.4	−14.0 ± 18.8	−19.5 ± 18.1	−16.6 ± 18.5	−18.8 ± 20.2	−16.2 ± 19.5	0.142 (0.24)

Values are mean ± SD.
[a] *Significantly different from 10 km.h^{-1} ($P < 0.05$).*
[b] *Significantly different from the previous running velocity ($P < 0.05$).*
Significant ANOVA P-values are represented in bold.

for flight time were twice as large at all velocities, as also reported elsewhere (Karamanidis et al., 2003). In general, SA scores for horizontal force production parameters including braking and push-off phase durations, peak forces, and impulses were similar to those measured for spatiotemporal variables. Minimal differences between limbs during running across a wide range of velocities suggest that limbs may not be used preferentially for braking or propulsion. However, mean SA scores above 3% were found for mean loading rate and spring mass model variables for all velocities, as also observed when running at 16 km.h^{-1} (Pappas et al., 2015), indicating that asymmetry increases in variables derived from the vertical force signal. Rumpf et al. (2014) also showed that asymmetries in vertical force (∼20%) are significantly greater than those of the horizontal force (∼15%) during a 30-m sprint on a non-motorized force treadmill. In contrast, up to three times larger deviations from symmetry were detected for mean horizontal compared to vertical forces during maximal treadmill sprinting, during both the early (Brown et al., 2017) and late (Girard et al., 2017a) acceleration phases. In this study using a wide range of running velocities, kinetic asymmetries tended to be larger than temporal ones at the fastest velocities, a finding also reported elsewhere (Exell et al., 2012a). A qualitative inspection of the average bilateral asymmetries further indicates that maximal downward vertical displacement was the only mechanical variable exceeding 10% (i.e., 11.2 ± 6.0%) across velocities. Anecdotally, our unique set

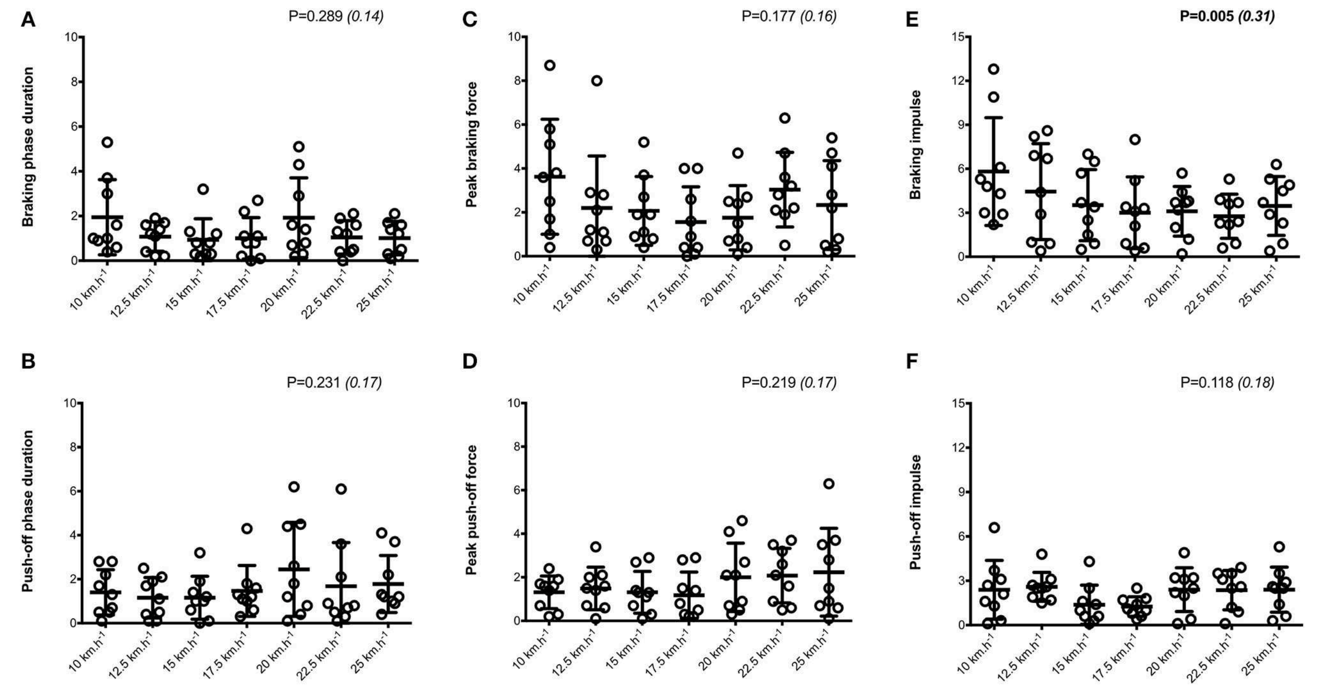

FIGURE 6 | Symmetry angle scores (expressed as %) for horizontal force production variables. Braking and push-off phases duration (**A,B**, respectively); Peak braking and push-off forces (**C,D**, respectively); Braking and push-off impulses (**E,F**, respectively). Values are mean ± SD. *P*-value and partial eta-squared in parentheses for the ANOVA main effect of running velocity.

TABLE 4 | Relative changes for horizontal force production variables between 10 and 25 km.h^{-1} ($n = 9$).

Variables (% change in reference to 10 km.h^{-1})	12.5 km.h^{-1}	15 km.h^{-1}	17.5 km.h^{-1}	20 km.h^{-1}	22.5 km.h^{-1}	25 km.h^{-1}	*P*-value (Effect size)
Braking phase duration	−11.4 ± 3.8[a]	−16.5 ± 4.8[ab]	−21.8 ± 5.5[ab]	−34.3 ± 5.7[ab]	−40.3 ± 3.9[a]	−43.8 ± 4.9[a]	<0.001 (0.95)
Peak braking force	33.8 ± 16.2[a]	44.2 ± 15.7[a]	61.0 ± 28.1[a]	77.8 ± 42.6[a]	89.9 ± 48.5[a]	105.5 ± 43.5[a]	<0.001 (0.82)
Braking impulse	18.0 ± 6.1	30.8 ± 8.4[ab]	42.7 ± 9.5[ab]	52.8 ± 13.5[ab]	61.5 ± 16.7[ab]	62.4 ± 17.3[a]	<0.001 (0.93)
Push–off phase duration	−11.4 ± 5.8[a]	−21.7 ± 4.0[ab]	−30.2 ± 6.9[ab]	−31.6 ± 7.0[a]	−36.2 ± 5.4[a]	−43.0 ± 5.1[a]	<0.001 (0.95)
Peak push–off force	39.7 ± 8.5[a]	70.4 ± 5.3[ab]	104.4 ± 11.2[ab]	141.6 ± 17.3[ab]	184.2 ± 29.9[ab]	197.5 ± 35.7[a]	<0.001 (0.97)
Push–off impulse	17.3 ± 8.6[a]	29.3 ± 10.0[ab]	39.9 ± 10.8[ab]	50.3 ± 14.8[ab]	59.8 ± 18.9[ab]	60.3 ± 20.2[a]	<0.001 (0.93)

Values are mean ± SD.
[a] *Significantly different from 10 km.h^{-1} ($P < 0.05$).*
[b] *Significantly different from the previous running velocity ($P < 0.05$).*

of data establishes preliminary normative data for describing patterns of lateralization across a wide range of running velocities and for a large number of mechanical variables in non-injured individuals. However, there is no definitive answer as to which level asymmetries really describe true differences between limbs. Whereas some groups have considered inter-limb differences significant only if the asymmetry score is >10% (Zifchock et al., 2006, 2008), others suggest that asymmetry must exceed intra-limb variability to be considered significant (Exell et al., 2012b). These data reinforce the notion that asymmetry is task- and variable-dependent and highlight limitations in applying arbitrary thresholds to determine acceptable between-limb differences.

Asymmetry Scores and Between-Participant's Variability

Whereas key gait variables displayed symmetrical gait overall, the individual nature of asymmetry was demonstrated by the relatively large range of asymmetry between participants for some variables (e.g., ∼0–10 and ∼0–20% for leg stiffness and vertical stiffness, respectively), across the range of velocities tested. This reinforces the importance of assessing asymmetry on an individual basis rather than using group means as athletes use different mechanisms for contralateral limbs to achieve similar outcomes (Exell et al., 2012b). Our SA data also demonstrate that patterns of change across different velocities are consistent between limbs for some but not all parameters, as shown by low-to-moderate correlations coefficients between selected variables. In general, significant relationships were observed between variables that are intrinsically linked; i.e., aerial time with step frequency ($r = 0.86$; $P < 0.01$) and either peak vertical force ($r = 0.67$ $P < 0.01$) or maximal downward vertical displacement ($r– = 0.98$; $P < 0.01$) with vertical stiffness. Testing asymmetry during maximal sprint performance in 11–16 year old boys, Meyers et al. (2017) reported weak yet significant relationships ($r = -0.24$ to 0.39; $P < 0.05$) between sprint velocity and a variety of asymmetry metrics including step frequency, step length, flight time, and vertical stiffness. The results of the current study also only partially agree with those of Belli et al. (1995). Indeed, the highest standard deviations exhibited by the kinetic (e.g., maximal downward vertical displacement, leg stiffness) and kinematic (e.g., contact time, braking phase duration) parameters were not always observed at the fastest velocity. Athletes and their support staff should be careful not to infer the presence of asymmetry based on a single or limited number of measurements given the variable nature of asymmetry evident in our study and those of others (Bishop et al., 2019).

Changes in Running Mechanical Variables Across Velocities

Our entire set of mechanical data and the trends for changes in the main biomechanical variables are within the range of those encountered in the literature for similar external conditions. For example, from 10 to 20 km.h^{-1} stride length increased by 78.5% and stride frequency by 12.6%. These values are comparable in magnitude to those reported elsewhere (∼77 and ∼17%, respectively) for team-sport athletes running at similar velocities on the same instrumented treadmill (Girard et al., 2017b). This confirms that running velocity increases mainly by lengthening stride in the range of submaximal velocities tested here, while stride frequency becomes more important at faster velocities ($>$ 25 km.h^{-1}) (Brughelli et al., 2011) and that is also associated with a 2-fold increase in vertical loading rates (Breine et al., 2014). Furthermore, our data displayed a linear reduction in contact time from the slowest to fastest velocities, while aerial time lengthened from 10 to 15 km^{-1} with no meaningful change thereafter. Similar to previous studies (Brughelli et al., 2011), peak vertical forces remained relatively constant when velocity increased from 20 km.h^{-1} and beyond, while there was no plateau of either peak braking force or push-off force both increasing linearly with velocity. We add the interesting observation that pushing more rather than braking less (in terms of peak forces) is the natural strategy used to increase running velocity from 10 to 25 km.h^{-1}. Indeed, with treadmill velocity increase, the magnitude of change for peak push-off force was twice as large as peak braking force, yet with similar corresponding decrements in braking and push-off phase durations. While braking time does not decrease nearly as much as push time as velocity increases from $<$ 5 km.h^{-1} to $>$ 20 km.h^{-1} (Cavagna, 2006), durations of the two phases in the range 10–20 km.h^{-1} is relatively similar.

By modeling the lower limb as a linear mass-spring system, mechanical spring constants can be used to describe the resistance of either center of mass vertical displacement or leg compression to a corresponding vertical force, known as vertical and leg stiffness, respectively (Brughelli and Cronin, 2008). Whereas, leg stiffness modifications were not significant across the range of velocities tested here, vertical stiffness was the spring mass model variable that displayed larger relative changes. Interestingly, the relative increase in peak vertical force only represented half of the decrease in maximal downward vertical displacement. These changes were almost identical to those of other trained runners tested at similar treadmill velocities (Brughelli et al., 2011). As velocity increases, higher stiffness values indicate that the center of mass undergoes smaller vertical displacement when confronted with an applied vertical force.

Limitations and Additional Considerations

In the present study we only examined nine healthy runners, which may limit the generalization of our results to a broader (i.e., previously injured) population, even though we found moderate-to-large effect sizes in general. Marked asymmetry in vertical force (but not contact times) during running in ACL reconstructed soccer players exist <9 months post-surgery, with these asymmetries also appeared to slightly increase with increasing speed, despite meeting functional criteria for return to sport (Thomson et al., 2018). Using a larger sample, it might be useful to examine if measures of asymmetries are evident more superiorly in rear-foot (as most marathon runners during the 2017 IAAF World Championships; Hanley et al., 2019) compared to forefoot or mid-foot strikers. Second, it cannot be ruled out that treadmill running may have artificially masked gait asymmetry. Treadmill compared to overground running that prevent any conscious or unconscious targeting of the force plates by the participants (the sampling effect), and thereby produce inherently low movement variability, also leads to improvement in SA scores at least in patients with knee osteoarthritis (Robadey et al., 2018). Using a treadmill allows for running velocity to be strictly controlled and maintained compared to outdoor running. However, most runners prefer running overground over running on a treadmill, especially when running at faster velocity, as this practice often is perceived as less comfortable (Miller et al., 2019). Perhaps the adaptation of our participants to treadmill running was to increase stride length at the higher velocities as opposed to stride frequency. Foot-worn inertial sensors for reliable detection of running gait temporal events (stride temporal parameters) may be useful to verify these assumptions and offer direct comparisons with data obtained under ecological situations (Falbriard et al., 2018). Third, it remains of particular interest to determine how gait asymmetries are influenced by the type of ground and how the effects of various external factors [i.e., fatigue (Radzak et al., 2017), footwear (Vagenas and Hoshizaki, 1992), training experience (Cavagna et al., 1977), limb dominance (Potdevin et al., 2008), and/or gait retraining with real-time feedback (Dingwell et al., 1996)] may be dependent on the running velocity at which they are assessed. In particular, the effect of footwear with different midsole thickness on SA scores in relation to running velocity changes warrants further consideration since this has the potential to influence running mechanics (Hamill and Gruber, 2017). Finally, we did not measure lower limb joint kinematics in this study and thus the effect of running velocity on the contribution that is made by individual joints (and potential neuro-mechanical compensations between joints; Brughelli and Cronin, 2008) is unclear.

CONCLUSION

The results of the current study showed large variability in SA scores across running mechanical parameters, and these values are largely unaffected by increasing running velocity from 10 to 25 km.h^{-1}. These data indicate that faster running velocities have no meaningful influence on the sensitivity of detecting gait asymmetries in non-injured, well trained runners.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

This studies involving human participants were reviewed and approved by Anti-Doping Laboratory Ethics Committee in Qatar (IRB Application Number: E2015000073). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

OG and NT conceived and designed the study. OG, PR, and NT conducted the experiments. All authors analyzed the data and drafted the manuscript, approved the manuscript.

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A 100-m Sprint Time Is Associated With Deep Trunk Muscle Thickness in Collegiate Male Sprinters

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Introduction: One reason athletes train their trunk muscles is that the body's trunk stability has been shown to prevent injury. However, the relationship between body trunk muscle thickness, particularly that of deep muscles, and athletic performance remains to be clarified.

Purpose: We aimed to explore the relationship between 100-m sprint performance and the sizes of the trunk stabilizing muscles, the psoas major muscle (PM), transversus abdominis (TA), and multifidus muscle (MM), in collegiate sprinters.

Methods: Fourteen male sprinters belonging to a university athletics club participated in this study. The thicknesses of the TA and MM were measured using an ultrasonic diagnostic apparatus (ProSound C3; Aloka, Tokyo, Japan). The cross-sectional area of the PM was assessed by a magnetic resonance imaging apparatus (Vantage Elan; Toshiba Medical Systems, Tokyo, Japan). The relationship between these anthropometric parameters and the 100-m sprint time was analyzed by Spearman's correlation coefficient, multi- regression analysis, and the change-point regression model.

Results: The sizes (mean ± SD) of the muscles were: PM, 43.074 ± 7.35 cm^2; TA, 4.36 ± 0.72 mm; and MM, 3.99 ± 0.48 cm. The mean 100-m sprint time was 11.00 ± 0.48 s. Spearman's correlation analysis revealed that the 100-m sprint time had a significant moderate negative correlation with TA ($\rho = -0.691$, $p < 0.01$) and a low negative but not significant correlation with MM ($\rho = -0.327$, $p = 0.28$), whereas PM did not show a significant or in-negligible correlation. The change-point regression model found the change-points in the 100-m sprint time and the thickness of the TA and MM at 4.70 mm (95% CI: 4.00–5.43 mm) and 3.84 cm (95% CI: 3.28–4.31 cm), respectively. The sprint time decreased with an increase in the thickness of the muscles up to the change-points, whereas it did not change even if the muscles became thicker than the change-points. The change-points were consistently observed when the thickness of the muscles was normalized by body mass.

Conclusion: Sprint performance for 100-m was found to be associated with TA and MM thickness in a biphasic manner. As muscle thickness increased, the sprint time decreased, followed by a plateau phase.

Keywords: multifidus muscle, transversus abdominis, sprint performance, change-point regression model, collegiate athletes

INTRODUCTION

The athletic 100-m sprint is one of the most popular events at the Olympic Games, where leading sprinters from around the world compete. Evaluation of the top 100-m sprinters shows that the key factors affecting 100-m sprinting performance are high sprinting speed and abilities to generate explosive acceleration and maintain high sprinting speed (Majumdar and Robergs, 2011). Additionally, anteroposterior force/power and horizontal force have been reported to be involved in the sprinting speed up to 40 m (Rabita et al., 2015). The factors that generate these forces are classified as controllable and uncontrollable factors: the controllable elements primarily include height, limb length, and cross-sectional muscle area (Rabita et al., 2015).

In recent years, the body trunk has attracted attention in terms of performance improvements and injury prevention (Zattara and Bouisset, 1988; Leetun et al., 2004) Indeed, the muscles located in the body trunk are at the center of all motor chains and are important for the stability of the spine and pelvis (Putnam, 1993). In addition, the trunk muscles play an important role in providing proximal stability for distal mobility and limb functions during sporting activities (Kibler et al., 2006; Reed et al., 2012). In particular, the deep trunk muscles, including the transversus abdominis (TA) and multifidus muscle (MM), are involved in the stability of the trunk and are activated prior to the movement of the limbs (Hodges and Richardson, 1997a) in order to support the limb's power during motor chain activity (Butcher et al., 2007; Jamison et al., 2012). In addition, the psoas major muscle (PM) is suggested to stabilize the trunk as well as hip flexion (Santaguida and McGill, 1995). Therefore, deep trunk muscles provide a fundamental basis for the strength of the extremities, by acting in advance of other muscles, and thus affect sports performance.

Hibbs et al. (2008) suggested that an improvement of sports performance requires muscle hypertrophy in the trunk muscles. Only weak-to-moderate correlations were found between the core strength assessed by the endurance of the torso stabilizing muscles and sports performance (e.g., sprint run and jump; Nesser et al., 2008; Okada et al., 2011), which seems to negate the importance of core strength training for improving sports performance. However, this research assessed the endurance of the deep trunk muscles instead of hypertrophy. As such, it is necessary to evaluate morphological muscle hypertrophy in deep trunk muscles and determine their relationship with sports performance. The association of sprint performance with the size of the PM located in the deep part of the trunk has been previously reported (Hoshikawa et al., 2006; Ema et al., 2018), and most previous studies on sports performance and trunk muscles evaluated functional muscle strength and trunk stability (Nesser et al., 2008; Sharrock et al., 2011; Shinkle et al., 2012). Thus, the relationship between deep trunk muscle morphology and sports performance has not been investigated for other muscles. Based on the above findings, we hypothesized that the 100-m sprint performance correlates with the size of the deep trunk muscle.

Therefore, in this study, we aimed to explore the relationship between 100-m sprint performance and the cross-sectional area of PM and muscle thicknesses of the TA and MM associated with trunk stability in collegiate sprinters.

MATERIALS AND METHODS

Participants

The participants of this study were 14 male sprinters who belonged to a university athletics club. Their age, height, and body weight (mean $\pm$ SD) were 20.1 $\pm$ 1.8 years, 172.0 $\pm$ 5.2 cm, and 65.6 $\pm$ 4.8 kg, respectively. Prior to the experiment, they were informed of the purpose, methods, and possible risks of this study. All participants provided written consent. This study was conducted with the approval of the Juntendo University Graduate School Ethics Committee (Approval number: #23-85).

Muscle Thickness

Muscle thickness was measured using an ultrasonic diagnostic apparatus (ProSound C3; Aloka, Tokyo, Japan) using the B mode.

TA

For the TA, participants lay on their backs and opened their lower limbs so that their thighs were parallel, with both shoulder joints at a 20–30 degrees transposition. The probe was placed at an inward position from the intersection point on the umbilical line and the underline of the lordosis (Hodges and Richardson, 1997b). The thickness (mm) of the TA was measured while confirming the image (**Figure 1**).

MM

For the MM, participants lay in prone position and set the thighs parallel. The probe of the ultrasonic diagnostic device was placed on the side of the spinous process of the L4–L5 intervertebral joint, and the longitudinal image of MM was confirmed parallel to the spine (Hides et al., 1995). The thickness (cm) of the MM was measured while confirming the image (**Figure 2**).

Cross-Sectional Area of the PM

A 1.5-T magnetic resonance imaging apparatus (Vantage Elan; Toshiba Medical Systems, Tokyo, Japan) was used for large psoas muscle cross-sectional imaging. T2-weighted images (FE method, TE: 90 ms, TR: 2,500 ms, matrix: 160 $\times$ 256, FOV: 320 $\times$ 32 mm, slice thickness 5 mm) of the central horizontal cross section between the fourth and fifth lumbar vertebrae were taken

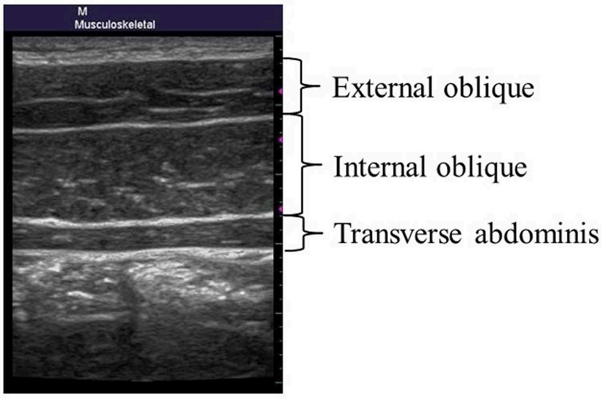


FIGURE 1 | Measurement site of the transverse abdominis.

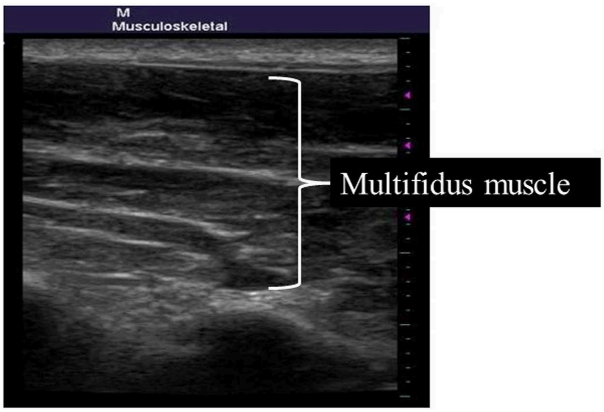


FIGURE 2 | Measurement site of the multifidus muscle.

(Hoshikawa et al., 2006). The cross-sectional area (cm^2) was calculated using image analysis software (OsiriX, 5.8.2, Pixmeo, Bernex, Switzerland). The sum of the left and right legs was used for the analysis.

Statistical Analysis

All data are expressed as the mean ± SD, with the exception of 95% confidential interval (95% CI). For continuous variables, correlations were reported as Spearman product moment correlations. The statistical significance was set at $p < 0.05$. Mukaka's rule was used for the interpretation of the size of the correlation coefficient (Mukaka, 2012).

A change-point regression model (CPRM) was used to identify the optimal splitting point of the linear regression line (Hayamizu et al., 2009; Matsui et al., 2011). We estimated the point at which the time of the 100-m sprint became saturated using the CPRM. Akaike's information criterion (AIC) is a statistical value to express the goodness-of-fit in a model by imposing a penalty for increasing the number of parameters (Akaike, 1998). We used AIC to assess the goodness-of-fit in the models between the simple regression model and the CPRM for determining the presence/absence of the saturated points.

TABLE 1 | Characteristics of the study participants.

			95% CI	
		Mean ± SD	**Lower**	**Upper**
Age	years	20.1 ± 1.9	19.0	21.2
Height	cm	172.0 ± 5.2	168.9	175.2
Body weight	kg	65.6 ± 4.8	62.7	68.5
100-m sprint time (season best)	s	11.0 ± 0.5	10.7	11.3
Psoas major (Cross-sectional area)	cm^2	43.1 ± 7.4	38.6	47.5
Transversus abdominis (thickness)	mm	4.4 ± 0.7	3.9	4.8
Multifidus muscle (thickness)	cm	4.0 ± 0.5	3.7	4.3

TABLE 2 | Spearman's correlation coefficients between 100-m sprint time and anthropometric parameters.

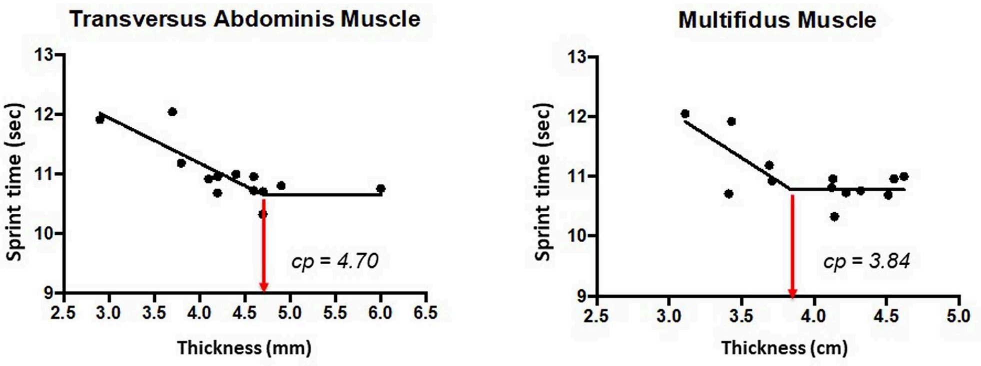
	ρ	p
Psoas major (cross-sectional area)	−0.226	0.46
Transversus abdominis (thickness)	−0.691	<0.01
Multifidus muscle (thickness)	−0.327	0.28

Analyses were performed using R3.3.1 (R Core Team, 2018) and GraphPad Prism 6 software (GraphPad Software, San Diego, CA, USA).

RESULTS

The characteristics of the study participants are shown in **Table 1**. The cross-sectional area of the PM and thicknesses of TA and MM were 43.074 ± 7.35 cm^2, 4.36 ± 0.72 mm, and 3.99 ± 0.48 cm, respectively. The mean 100-m sprint time was 11.00 ± 0.48 s. Spearman's correlation analysis found that 100-m sprint time had a significant moderate negative correlation with thickness of TA ($\rho = -0.691$, $p < 0.01$) and a low negative but not significant correlation with thickness of MM ($\rho = -0.327$, $p = 0.28$), whereas PM did not show a significant or in-negligible correlation (**Table 2**).

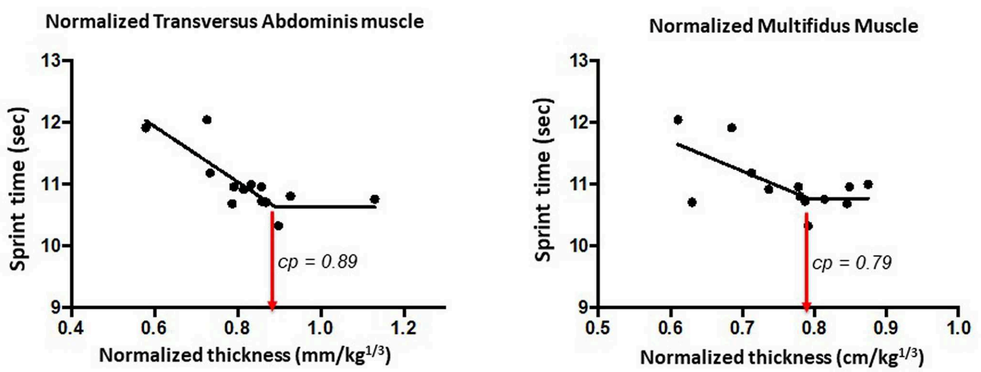
The scatter plot of the 100-m sprint time and the thickness of the TA and MM depicted a biphasic relationship. Specifically, the sprint time decreased depending on the muscle thickness to a certain level, but the time became constant when the thickness became beyond a certain change-point. Therefore, we examined the CPRM for the presence of the change-points. The AICs of the CPRM were smaller than those of the simple regression model in both cases, which confirmed the presence of the change-points. The change-points of the TA and MM were estimated to be 4.70 mm (95% CI: 4.00–5.43 mm) and 3.84 cm (95% CI: 3.28–4.31 cm), respectively (**Figure 3**). The change-points were consistently observed when the thickness of the TA and MM was normalized by body mass: 0.98 mm/kg$^{1/3}$ (95% CI: 0.78–1.00 mm/kg$^{1/3}$) for TA and 0.79 cm/kg$^{1/3}$ (95% CI: 0.65–0.93 cm/kg$^{1/3}$) for MM (**Figure 4**). The stability of the change-points was confirmed by leave-one-out cross-validation, in which data sets were analyzed after excluding one participant's data for each analysis. As this study had 13 participants, we analyzed 13 data



1[st] line: y = -0.76x + 14.23
2[nd] line: y = 10.66
Change point: 4.70 (95%CI: 4.00, 5.43)
R^2: 0.71

1[st] line: y = -1.56x + 16.76
2[nd] line: y = 10.77
Change point: 3.84 (95%CI: 3.38, 4.31)
R^2: 0.58

FIGURE 3 | Mean profiles of the change-point regression model for the 100-m sprint time and the thickness of the TA and MM.



1[st] line: y = -4.49x + 14.64
2[nd] line: y = 10.66
Change point: 0.89 (95%CI: 0.78, 1.00)
R^2: 0.69

1[st] line: y = -4.85x + 14.61
2[nd] line: y = 10.80
Change point: 0.79 (95%CI: 0.65, 0.93)
R^2: 0.43

FIGURE 4 | Mean profiles of the change-point regression model for the 100-m sprint time and the thickness of the TA and MM normalized by body mass.

sets in the same manner for TA and MM with and without normalization by body mass.

In contrast, no change-point was observed between sprint time and cross-sectional area of PM with and without normalization by body mass (results not shown).

DISCUSSION

This study aimed to explore the relationship between the 100-m sprint time and the morphology of the deep trunk muscles in collegiate athletes. Sprint time exhibited a change-point at which the time decreased as the muscle thickness of the TA and MM increased, followed by a plateau phase; even if they became thicker. Thus, thickness of the trunk muscles did not show a simple linear correlation with the 100-m sprint time.

In this study, no correlation was found between the cross-sectional area of the PM and 100-m sprint time. Some studies have investigated junior athletes to demonstrate the association between the cross-sectional area of the PM and sprint performance (Hoshikawa et al., 2006; Tottori et al., 2018). Tottori et al. (2016) investigated sprinters and mid-distance runners of the same age as the present study; however, their sprint performance levels were lower compared with those of the participants of this study. In addition, the PM size of participants in this study (21.5 ± 3.7cm^2) was larger than those measured by Hoshikawa et al. (2006) (17.1 ± 2.6 cm^2) and Tottori et al. (2018) (8.6 ± 2.4 cm^2). Kubo et al. (2011) reported that there was no relationship between sprint acceleration ability and cross-sectional area of PM, which is similar to the findings obtained in this study. Ema et al. (2018) demonstrated the importance of the PM, investigating the relation between actual running motion and muscle volume (not muscle size). Therefore, the muscle volume of PM instead of muscle size could be associated with sprint performance. Because there are few studies focusing on muscle volume, further research on sprint performance and muscle volume of PM should be conducted in adult sprinters with high sprint performance.

Previous studies have demonstrated the relationship between sprint performance and the extensor-flexor strength of the knee or hip (Alexander, 1989; Dowson et al., 1998). Hoshikawa et al. (2006) reported that 100-m sprint time was dependent on the PM-to-quadriceps femoris ratio rather than their absolute sizes. Another recent study found that the sizes of the thigh and PM, particularly the rectus femoris, may play an important role during the swing phase of sprinting (Ema et al., 2018). However, Spearman's correlation analysis showed that, instead of the PM, the deep trunk muscles, TA and MM had significant correlations with sprint performance. The TA and MM are classified as local muscles. The contraction of the TA enhances intra-abdominal pressure and thoracolumbar fascia tension (Cresswell et al., 1992). Elevated intra-abdominal pressure and thoracolumbar fascia tension work together to stabilize the spine (Gracovetsky et al., 1977). In addition, the contraction of the MM controls segments of the lumbar spine (Panjabi et al., 1989). Therefore, the TA and MM both might contribute toward stabilizing the spine and pelvis by controlling the intra-abdominal pressure (Cresswell et al., 1992), thoracolumbar fascia tension (Gracovetsky et al., 1977; Cresswell et al., 1992), and lumbar segments (Panjabi et al., 1989), and maintain the pelvis in an optimal position or posture for the running motion (Barr and Lewindon, 2014).

The activities of the muscles located from the shoulder to the pelvis have been shown to be important for transferring power from the larger torso to the smaller limbs (Stephenson and Swank, 2004). In addition, the 5,000 m running time of healthy adults was reported to improve with upper body training (Sato and Mokha, 2009). In contrast, some reports negate the importance of trunk training in sports performance (Nesser et al., 2008; Okada et al., 2011). However, previous studies have not investigated the thickness of deep trunk muscles. Here, we measured the muscle thickness of the deep trunk muscles to determine the importance of the trunk muscles in sprint performance.

Our findings demonstrated the existence of a change-point in the relationship between 100-m sprint time and the thickness of the TA and MM in both the actual thickness and thickness normalized by body mass. A possible reason for the change-point is the relationship between sprint time and physical load. In the sprint time up to 10.6 s, maintenance of trunk stability by the TA and MM contributes to performance; while in the time faster than 10.6 s, the increased physical load requires the contribution of other muscles in addition to TA and MM, e.g., abdominal oblique muscles and erector spinae. In fact, the anthropometric features of the 100-m finalists at the Olympics and World Championships apparently differ from those of the participants of this study. The mean height, body weight, body mass index, and 100-m sprint time were 176 $\pm$ 3.6 cm, 76.7 $\pm$ 6.4 kg, 25.5 $\pm$ 2.3 kg/m^2, and 9.96 $\pm$ 0.5 s at the Beijing Olympics (2008); 177.3 $\pm$ 6.4 cm, 79.0 $\pm$ 8.0 kg, 22.5 $\pm$ 2.2 kg/m^2, and 9.91 $\pm$ 0.10 s at the Berlin World Athletics Championships (2009); and 179.4 $\pm$ 8.1 cm, 80.4 $\pm$ 8.2 kg, 24.9 $\pm$ 1.5 kg/m^2, and 9.86 $\pm$ 0.10 s at the London Olympics (2012) (Krzysztof and Mero, 2013). However, limited research makes it difficult to interpret this finding on local muscles and sprint performance. Accordingly, it is necessary to confirm whether the change-point can be observed in sprinter groups whose competition levels are higher/lower than the participants of this study.

The present study has some limitations. As we assessed the members of a university athletics club, the number of participants and diversity of their competition levels were limited. In order to minimize the impact of the small number of the participants, we performed leave-one-out cross-validation in CPRM and confirmed that stable results were obtained among the participants. However, further studies are warranted to validate the results. The extensor-flexor strengths of trunk muscles were not measured. The muscle strength can be estimated from muscle thickness (Muraki et al., 2013). However, in trunk muscles, the relationship between thickness and strength is not significant, suggesting that trunk muscle thickness may not directly affect muscle strength (Ishida et al., 2019). Therefore, further studies are warranted to determine the relationship of the TA and MM with sprint performance, considering anthropometric and muscle function (strength and power).

In this study, the local muscles, TA and MM, were shown to contribute to sprint performance for the first time. In addition, the existence of change-points indicates that simply aiming for the hypertrophy of these muscles would not be an effective strategy. These findings should provide important implications for sprint training.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the manuscript/supplementary files.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Juntendo University Graduate School Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SF, SK, and KSakum: conceptualization. YSuz, YA, and KH: formal analysis. SF, SK, and AK: investigation. SF, AK, and KSakur: methodology. KSakum and KSakur: resources and supervision. SF, SK, YSug, and KH: writing–original draft. SF, YSuz, KH, and MS: writing–review and editing.

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Kinematics of Maximal Speed Sprinting With Different Running Speed, Leg Length, and Step Characteristics

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This study aimed to provide multiple regression equations taking into account differences in running speed, leg length, and step characteristics to predict kinematics of maximal speed sprinting. Seventy-nine male sprinters performed a maximal effort 60-m sprint, during which they were videoed through the section from the 40- to 50-m mark. From the video images, leg kinematic variables were obtained and used as dependent variables for multiple linear regression equation with predictors of running speed, leg length, step frequency, and swing/support ratio. Multiple regression equations to predict leg kinematics of maximal speed sprinting were successfully obtained. For swing leg kinematics, a significant regression model was obtained to predict thigh angle at the contralateral foot strike, maximal knee flexion and thigh lift angular velocities, and maximal leg backward swing velocity (adjusted $R^2 = 0.194$–0.378, medium to large effect). For support leg kinematics, a significant regression model was obtained to predict knee flexion and extension angular displacements, maximal knee extension velocity, maximal leg backward swing angular velocity, and the other 13 kinematic variables (adjusted $R^2 = 0.134$–0.757, medium to large effect). Based on the results, at a given leg length, faster maximal speed sprinting will be accompanied with greater thigh angle at the contralateral foot strike, greater maximal leg backward swing velocity during the swing phase, and smaller knee extension range during the support phase. Longer-legged sprinters will accomplish the same running speed with a greater thigh angle at contralateral foot strike, greater knee flexion range, and smaller maximal leg backward swing velocity during the support phase. At a given running speed and leg length, higher step frequencies will be achieved with a greater thigh angle at contralateral foot strike and smaller knee flexion and extension ranges during the support phase. At a given running speed, leg length and step frequency, a greater swing/support ratio will be accompanied with a greater thigh angle at contralateral foot strike and smaller knee extension angular displacement and velocity during the support phase. The regression equations obtained in this study will be useful for sprinters when trying to improve their maximal speed sprinting motion.

Keywords: running motion, multiple regression analysis, athletics, step frequency, biomechanics

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INTRODUCTION

Maximal speed during a 100-m race is strongly related to total race time (Slawinski et al., 2017). Therefore, maximal speed sprinting is of great importance for a 100-m race. In addition, the potential to run at greater maximal speed will improve performance for 200- and 400-m races and also the long- and triple jumps (Hanon and Gajer, 2009; Koyama et al., 2011; Panoutsakopoulos et al., 2016). Accordingly, examining the determinants of maximal speed sprinting performance is valuable not only for improving 100-m race performance but also for enhancing performance in other events.

Associations of leg kinematics and maximal speed sprinting performance have broadly been investigated (Kunz and Kaufmann, 1981; Alexander, 1989; Ae et al., 1992; Bushnell and Hunter, 2007; Ito et al., 2008; Yada et al., 2011; Toyoshima and Sakurai, 2016; Haugen et al., 2018). For joint kinematics, greater maximal running speed was associated with more extended knee joint angle at the mid-support (Yada et al., 2011), smaller knee joint angle at toe-off (Bushnell and Hunter, 2007; Yada et al., 2011), greater minimal knee joint angle during the swing phase (Ito et al., 2008), greater hip extension velocity during the support phase (Ae et al., 1992; Ito et al., 2008), and smaller knee extension velocity during the support phase (Ito et al., 2008). For segmental kinematics, greater maximal running speed was associated with greater forward lean of the shank at toe-off (Yada et al., 2011), less forward lean of the thigh at toe-off (Yada et al., 2011), higher forward lean shank angular velocity at foot strike (Toyoshima and Sakurai, 2016), and greater maximal forward lean thigh angular velocity during the support phase (Alexander, 1989). Moreover, greater maximal running speed was accompanied with greater whole leg backward swing velocity at foot strike (Ae et al., 1992) and a smaller horizontal distance between the knees at foot strike (Bushnell and Hunter, 2007; Yada et al., 2011).

Although the aforementioned previous studies provided valuable knowledge of the important kinematic features for faster maximal speed sprinting, corresponding features would likely be different based on a specificity of individuals. Theoretically, longer leg length will produce greater endpoint velocity for a given angular velocity, but longer leg length is also typically accompanied by a greater moment of inertia. Thus, differences in leg length may produce differences in kinematics for faster maximal speed sprinting. In addition to leg length, combinations of step length and frequency, which is partly affected by the leg length, are factors that influence kinematics of faster maximal speed sprinting (Toyoshima and Sakurai, 2016). Accordingly, it is essential to investigate the association of kinematics of sprinting with maximal running speed, taking into account the step characteristics in addition to the leg length. Because stride frequency is an inverse of stride time and one stride consists of the support and swing phases, there can be various combinations of support and swing times (swing/support ratio) even if the stride frequencies of two sprinters are equal to each other. Consequently, considering not only the leg length but also these step characteristics (step frequency and swing/support ratio) will improve the understanding of the kinematics of faster maximal speed sprinting.

To investigate influences of the leg length and spatiotemporal variables, in addition to running speed, on leg kinematic variables, multiple regression analyses would be useful and allow us to evaluate magnitudes of changes in kinematic variables with manipulating running speed, leg length, and spatiotemporal variables. Knowledge of difference in magnitudes of changes in kinematic variables associated with changes in running speed, leg length, and spatiotemporal variables would be of great value to coaches when training a sprinter to improve maximal speed sprinting performance. Moreover, because each of previous studies investigated relationships between maximal speed sprinting performance and kinematic variables for small number of variables (Kunz and Kaufmann, 1981; Alexander, 1989; Ae et al., 1992; Bushnell and Hunter, 2007; Ito et al., 2008; Yada et al., 2011; Toyoshima and Sakurai, 2016; Haugen et al., 2018), the data as normative information which can be used by coaches and sprinters are limited. Adopting a large number of kinematic variables therefore would provide normative information for considering faster maximal sprinting performance based on individual-specific factors.

The purpose of this study was to provide multiple regression equations taking into account differences in running speed, leg length, and step characteristics to predict kinematics of maximal speed sprinting for understanding kinematics of faster maximal speed sprinting with the differences in leg length and step characteristics. In an applied environment, sprinters and coaches are trying to improve maximal speed sprinting performance based on individual-specific factors. Therefore, the findings of this study would help to provide information which could be used to inform individual-specific features of faster maximal speed sprinting.

MATERIALS AND METHODS

Participants

The participants were 79 male sprinters (mean ± SD: age, 20.7 ± 1.9 y; stature, 1.75 ± 0.05 m; body mass, 66.6 ± 5.0 kg; personal best 100-m time, 11.08 ± 0.42 s, ranging from 10.30 to 12.14 s). Written-informed consent was obtained from participants before participating in the study which was approved by the research ethics committee of the institute.

Experiments

After a self-selected warm-up, the participants performed a maximal effort 60-m sprint from a two-point standing position in spiked shoes. The participants were instructed to achieve their maximal speed during the section from the 40- to 50-m mark. The participants were videoed through the section from the 40- to 50-m mark using one panning camera (EX-F1, Casio, Tokyo, Japan, 300 Hz, 512 × 384 pixels). The camera was located 1 m above the ground and perpendicular to the 45-m mark from the start and was 45 m away from the center of the running lane. The camera field of view was approximately 4 m in the horizontal direction. Reference markers were placed every meter on both sides of the running lane from the 40- to 50-m mark. To ensure appropriate digital visualization of the segment coordinates, adhesive, black or white markers were attached to anatomical landmarks on the right fifth metatarsal head, ankle, knee, and greater trochanter.

Data Processing

Seven segment endpoints (toe, the fifth metatarsal head, heel, ankle, knee, and greater trochanter for the right leg and suprasternal) of each participant from five frames before the left leg foot strike to five frames after the next left leg foot strike (i.e., one stride, two steps) were manually digitized at 150 Hz using a Frame-DIAS system (Dkh, Tokyo, Japan). Foot strike and toe-off were visually identified three times by one examiner (all identifications being consistent). From the coordinates of the digitized endpoints and the closest four reference markers (forward and backward on both sides) in the same frame, 2-D coordinates of the endpoints in the sagittal plane were obtained. The reconstruction of the data using four reference markers was performed in reference to a previous study (Nagahara et al., 2014b). The estimated errors shown in a previous study, which was performed with similar experimental setting and used the same camera, was <9 mm (Nagahara et al., 2014b). The coordinates of the segment endpoints were smoothed using a Butterworth low-pass digital filter. The cut-off frequency (4.5–10.5 Hz) was decided using residual method proposed by Wells and Winter (1980). Using the reconstructed endpoint coordinates of the fifth metatarsal head, ankle, knee, and greater trochanter for the right leg and suprasternal, a 4-segment linked model comprising the right foot, right shank, right thigh and trunk was developed. In addition, the raw left toe coordinates at the left foot strikes before and after the investigated right leg support phase were obtained for calculating stride length.

Step length was defined as half of the length between the left toe locations of consecutive two steps. Stride time was the duration from one left foot strike to the next left foot strike, with step frequency determined as the inverse of one half of stride time. Running speed was computed as the product of step length and frequency. From the left foot strike, one stride cycle was divided into four phases (left leg support phase, left leg flight phase, right leg support phase, and right leg flight phase), and the time taken for each phase was obtained (**Figure 1**). Moreover, the right leg swing time was computed as sum of the times for left leg support, left leg flight, and right leg flight phases. In addition, swing/support ratio was obtained dividing the right leg swing time by right leg support time, and flight/support ratio was computed by dividing the sum of the right and left leg flight times by the sum of right and left leg support times. Right leg joint and segment angles were calculated using the aforementioned 4-segment linked model as shown in **Figure 1**. An extension of the joints was given a positive convention. Moreover, right leg joint and segment angular velocities were computed by differentiating the corresponding joint and segment angles. Leg length was obtained as sum of average thigh and shank lengths which were taken by the digitized data across the whole stride cycle in reference to a previous study (Toyoshima and Sakurai, 2016). In reference to variables used in previous studies (Kunz and Kaufmann, 1981; Alexander, 1989; Ae et al., 1992; Hunter et al., 2004; Bushnell and Hunter, 2007; Ito et al., 2008; Yada et al., 2011; Toyoshima and Sakurai, 2016; Haugen et al., 2018), the kinematic variables listed in **Table 1** were extracted.

Statistical Analyses

Simple linear regression analysis was used to test the relationship between stature (independent variable) and leg length (dependent variable), between swing/support ratio (independent variable) and flight/support ratio (dependent variable), and between running speed (independent variable) and leg length (dependent variable). Multiple linear regression analysis was used to examine the relationship of running speed and leg length (independent variables) with step frequency (dependent variable), of running speed, leg length, and step frequency (independent variables) with swing/support ratio (dependent variable), and of running speed, leg length, step frequency, and swing/support ratio (independent variables) with each of the kinematic variables (dependent variable). The significance level was $p < 0.05$. Threshold values for the interpretation of the adjusted R^2 as an effect size were set at 0.02 (small), 0.13 (medium), 0.26 (large) in accordance with Cohen (1988). All statistical values were calculated using SPSS statistical software (IBM, Tokyo, Japan). To evaluate the magnitudes of changes in kinematic variables with changes in each independent variable, the running speed, leg length, step frequency and swing/support ratio were manipulated using obtained regression equation in reference to a previous study (Hunter et al., 2004). The inputs were the mean and 2 standard deviation (SD) or 2 standard error of estimate (SEE) values for running speed and leg length or for step frequency and swing/support ratio. The 2 SD or 2 SEE was selected because 2 SD indicates that 95.45% of values lie within a band around the mean in a normal distribution. That is, using the range of 2 SD or 2 SEE covers changes in kinematics associated with realistic changes in running speed and leg length or step frequency and swing/support ratio. For the manipulation, variables with a medium or large effect size (based on adjusted $R^2 > 0.13$) were selected. The magnitudes of changes in kinematic variables with the manipulation were expressed as a ratio (percentage) in relation to mean value of each kinematic variable.

RESULTS

There were significant correlations between stature and leg length ($r = 0.843$, $p < 0.001$) and between swing/support ratio and flight/support ratio ($r = 0.916$, $p < 0.001$) (**Table 2**), while running speed was not correlated with leg length ($r = 0.186$, $p = 0.100$). Running speed and leg length combined in a significant regression model to predict step frequency (adjusted $R^2 = 0.382$, large effect). Running speed, leg length and step frequency combined in a significant regression model to predict swing/support ratio (adjusted $R^2 = 0.183$, medium effect).

For swing leg kinematics, running speed, leg length, step frequency, and swing/support ratio combined in a significant regression model to predict thigh angle at the contralateral foot strike, maximal thigh lift angle, maximal knee flexion angular velocity, maximal thigh lift angular velocity, and maximal leg

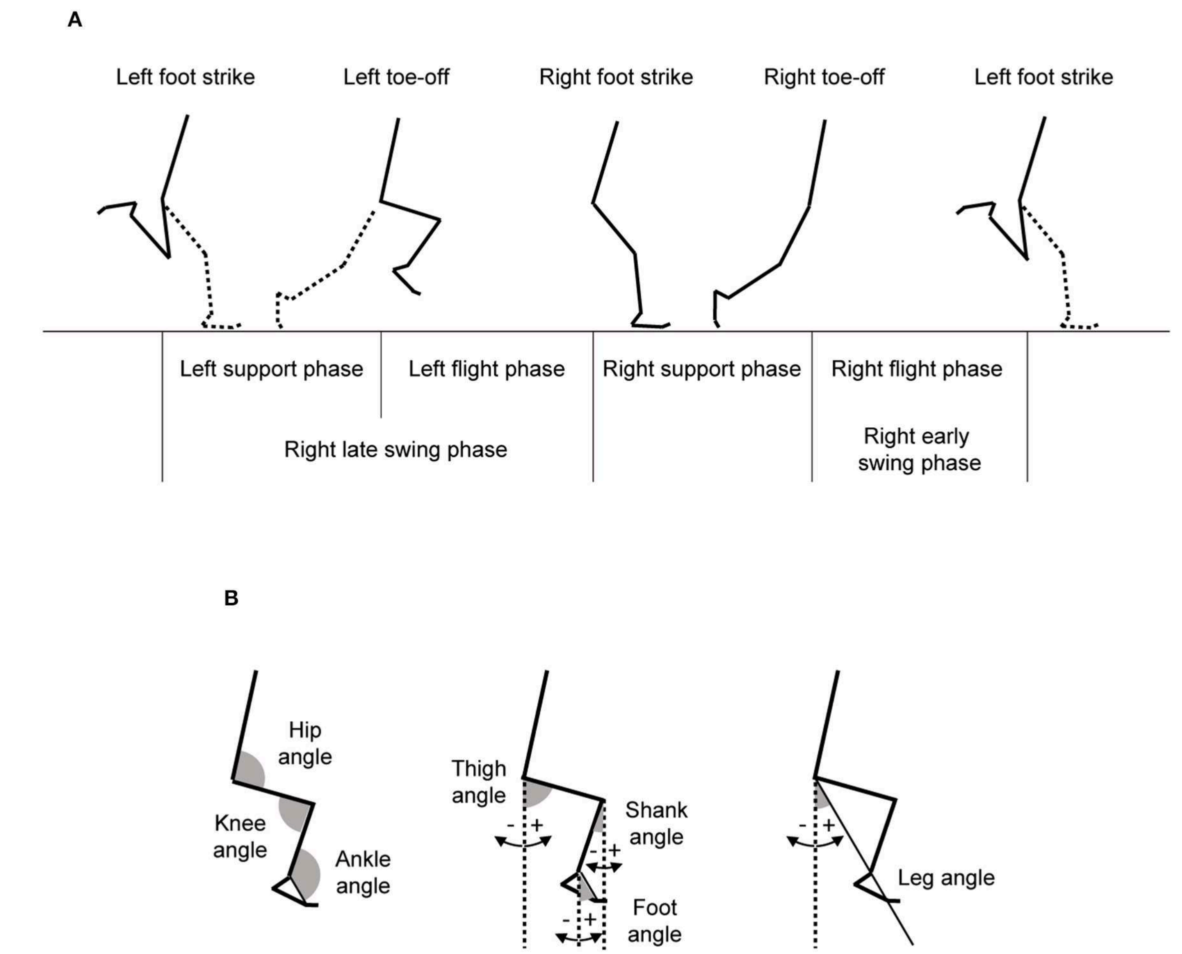

FIGURE 1 | Definition of the events and phases during one stride of maximal speed sprinting and definition of joint, segment, and leg angles.

backward swing velocity (adjusted $R^2 = 0.122$–0.378, small to large effect) (**Table 3**). For support leg kinematics, running speed, leg length, step frequency and swing/support ratio combined in a significant regression model to predict the relative foot strike distance, relative toe-off distance, hip, knee and ankle angles at the foot strike and toe-off, hip extension angular displacement, knee flexion and extension angular displacements, maximal hip, knee and ankle extension (plantar-flexion) angular velocities, thigh and shank angles at the ipsilateral foot strike and toe-off, foot angle at the ipsilateral toe-off, thigh, shank and foot angular displacements from foot strike to toe-off, and maximal leg backward swing angular velocity (adjusted $R^2 = 0.074$–0.757, small to large effect). For the minimum knee joint angle during the swing phase and ankle dorsi- and plantar-flexion angular displacements and foot angle at foot strike during the support phase, a significant regression was not obtained.

Table 4 shows four examples of 21 selected leg kinematic variables (i.e., those with a medium or large adjusted R^2) when each of the predictors changes. Comparing the changes in the values of the predicted kinematic variables among the four conditions with the same magnitude of changes in predictors (i.e., ±2SD for condition A and B, ±2SEE for condition C and D), the greatest changes were found in condition A for thigh angle at contralateral foot strike and maximal leg backward swing velocities during the swing and support phases (3 variables), in condition B for maximal knee flexion angular velocity and maximal thigh lift angular velocity (2 variables), in condition C for knee flexion angular displacement (1 variables), and in condition D for the rest of variables (15 variables).

DISCUSSION

This study aimed to provide multiple regression equations taking into account differences in running speed, leg length and step characteristics to predict kinematics of maximal speed sprinting for understanding kinematics of faster maximal speed sprinting with the difference in leg length and spatiotemporal variables. Employing a large number ($n = 79$) of sprinters across a broad range of performance levels (10.30–12.14 s), multiple regression equations which took into account difference in running speed, leg length and spatiotemporal variables to predict kinematics

TABLE 1 | Variables used in this study and descriptive statistics for each one based on the studied cohort.

Variables [units]		Mean	SD	Min.	Max.
Age [years]		20.7	1.9	18.0	27.0
Stature [m]		1.75	0.05	1.62	1.85
Body mass [kg]		66.6	5.0	48.4	79.0
100-m personal best time [s]		11.08	0.42	10.30	12.14
Leg length [m]		0.812	0.032	0.732	0.885
Spatiotemporal variables	Running speed [m/s]	9.90	0.46	8.83	10.97
	Step length [m]	2.15	0.11	1.88	2.37
	Step frequency [Hz]	4.60	0.22	4.17	5.17
	Stride time [s]	0.435	0.020	0.387	0.480
	Left support time [s]	0.103	0.007	0.087	0.120
	Left flight time [s]	0.112	0.009	0.093	0.133
	Right support time [s]	0.105	0.007	0.093	0.120
	Right flight time [s]	0.115	0.010	0.093	0.133
	Right swing time [s]	0.330	0.017	0.287	0.373
	Swing/support ratio	3.16	0.24	2.71	3.71
	Flight/support ratio	1.10	0.11	0.88	1.41
Swing leg kinematics	Thigh angle at contralateral foot strike [deg]	4.1	8.6	−17.7	22.9
	Minimum knee joint angle [deg]	31.6	5.6	22.1	47.3
	Maximal thigh lift angle [deg]	70.3	4.6	62.0	83.6
	Maximal knee flexion angular velocity [deg/s]	−1,185	92	−1,397	−874
	Maximal thigh lift angular velocity [deg/s]	792	47	641	887
	Maximal leg backward swing angular velocity [deg/s]	−466	50	−569	−349
Support leg kinematics	Relative foot strike distance (anteroposterior distance between hip and the fifth metatarsal head at foot strike/leg length × 100) [%]	49.8	3.6	39.7	56.9
	Relative toe-off distance (anteroposterior distance between hip and the fifth metatarsal head at toe-off/leg length × 100) [%]	72.4	3.9	62.6	83.0
	Hip angle at foot strike [deg]	131.9	3.7	123.7	140.0
	Knee angle at foot strike [deg]	152.3	5.6	140.3	166.5
	Ankle angle at foot strike [deg]	123.2	4.3	112.8	133.6
	Hip angle at toe-off [deg]	196.4	5.3	182.2	209.6
	Knee angle at toe-off [deg]	155.4	4.8	141.5	168.2
	Ankle angle at toe-off [deg]	147.3	4.5	136.3	156.7
	Knee flexion angular displacement [deg]	−13.6	3.6	−3.8	−20.9
	Ankle dorsiflexion angular displacement [deg]	−19.1	3.9	−7.6	−28.7
	Hip extension angular displacement [deg]	64.5	5.1	48.7	74.9
	Knee extension angular displacement [deg]	16.9	5.7	2.6	32.6
	Ankle plantarflexion angular displacement [deg]	43.2	3.8	36.2	55.7
	Maximal hip extension velocity [deg/s]	850	73	615	992
	Maximal knee extension velocity [deg/s]	443	118	98	726
	Maximal ankle plantarflexion velocity [deg/s]	1,009	92	798	1,236
	Thigh angle at foot strike [deg]	33.0	3.6	24.0	40.2
	Shank angle at foot strike [deg]	5.3	3.2	−3.0	14.5
	Foot angle at foot strike [deg]	62.1	3.6	53.7	69.4
	Thigh angle at toe-off [deg]	−28.7	3.6	−37.6	−15.7
	Shank angle at toe-off [deg]	−53.3	2.9	−61.0	−46.4
	Foot angle at toe-off [deg]	−20.6	4.7	−32.0	−10.1
	Thigh angular displacement [deg]	61.8	5.1	45.3	72.4
	Shank angular displacement [deg]	58.6	3.6	50.4	67.7
	Foot angular displacement [deg]	82.8	4.4	72.2	93.7
	Maximal leg backward swing angular velocity [deg/s]	−664	43	−751	−572

of maximal speed sprinting were successfully obtained, and leg kinematics of greater maximal running speed based on leg length and step characteristics were elucidated using the multiple regression equations. Although there were previous studies that examined the relationship between running speed and each of kinematic variables (Kunz and Kaufmann, 1981; Alexander, 1989; Ae et al., 1992; Bushnell and Hunter, 2007; Ito et al., 2008; Yada et al., 2011; Toyoshima and Sakurai, 2016; Haugen et al., 2018), this study is the first to demonstrate kinematic features for faster sprinting performance, taking into account the characteristics of individuals in terms of leg length and

TABLE 2 | Multiple regression equations to calculate leg length, flight/support ratio, step frequency, and swing/support ratio.

Dependent variables [units]	Multiple regression equations	p	SEE	R	R^2
Leg length [m]	Y = 0.519·Stat – 0.095	<0.001	0.017	0.843	0.707
Flight/support ratio	Y = 0.431·SSR – 0.261	<0.001	0.045	0.916	0.836
Step frequency [Hz]	Y = 0.236·RS – 3.320·LL + 4.965	<0.001	0.170	0.631	0.382
Swing/support ratio	Y = 0.255·RS – 2.624·LL – 0.547·SF + 5.288	<0.001	0.212	0.463	0.183

Stat, stature [m]; SSR, swing/support ratio; RS, running speed [m/s]; LL, leg length [m]; SF, step frequency [Hz]; SEE, standard error of estimate; R, multiple correlation coefficient; R^2, determination coefficient adjusted for the degrees of freedom.

spatiotemporal variables. Moreover, as the adjusted R^2 for all predicted kinematic variables were greater than R^2 for each of simple linear regression analyses (**Supplementary Table 1**), it is evident that not only running speed, but also leg length and spatiotemporal variables (step frequency and swing/support ratio), relate to leg kinematics.

Taking into account the significant correlations for stature and leg length, for swing/support ratio and flight/support ratio, and not for running speed and leg length, the regressions among the running speed, leg length, step frequency, and swing/support ratio demonstrate that faster running speed is associated with higher step frequency and greater swing (flight)/support ratio regardless of leg length (stature). The significant relationship for running speed and step frequency and not for running speed and leg length are supported by previous studies which employed a large number of participants (Ito et al., 2008; Nagahara et al., 2018b). Moreover, in line with a previous study (Nagahara et al., 2018b), the results indicate that the longer the leg length, the lower the step frequency and swing/support ratio, while the higher the step frequency, the lower the swing/support ratio. As moment of inertia theoretically increases with the square of the length for a given mass, a long leg length will make it difficult to rotate fast, resulting in a decrease in step frequency. In addition, a long leg length at a given running speed and step frequency will theoretically lead to long support time with long support distance. Because step frequency is an inverse of step time which consists of support and flight times, and support time at a given speed and leg length is difficult to change due to geometric constraints, higher step frequency through shorter step and flight times will be accompanied with lower swing/support ratio. Accordingly, it can be said that the aforementioned findings are theoretically reasonable.

Relative foot strike distance, hip, knee, and thigh angles at foot strike, hip angle at toe-off, and thigh angular displacement showed small percentage changes (<2%) in association with changes in running speed of ±2SD (**Table 4**). Thus, the influence of changes in running speed on these variables can be considered as negligible. For faster maximal speed sprinting with the same leg length, greater thigh angle at the contralateral foot strike, maximal knee flexion and thigh lift angular velocities, and maximal leg backward swing velocity can be considered as important kinematic features during the swing phase. While some important variables cannot be compared with previous studies, the importance of thigh angle at the contralateral foot strike and maximal leg backward velocity has been confirmed in previous studies (Ae et al., 1992; Bushnell and Hunter, 2007; Yada et al., 2011). Greater thigh lift angle at the contralateral foot strike and faster thigh lift angular velocity indicate faster recovery of the swing leg, and this motion can assist in the rapid production of vertical force, through upward acceleration of the swing leg that is essential for achieving high maximal speed sprinting (Weyand et al., 2000). Foot velocity in relation to the body center of mass during the support phase is equal to running speed, and as the whole leg angular velocity is one of the mechanical determinants of foot velocity, these results appear logical.

During the support phase, greater relative toe-off distance, smaller knee flexion and extension angular displacements, greater hip extension angular displacement, greater maximal hip extension and smaller maximal knee extension velocities, greater thigh and shank forward lean angles at toe-off, greater shank and foot angular displacements, and greater maximal leg backward swing velocity were defined as essential kinematic features for faster maximal speed sprinting with the same leg length based on magnitudes of the changes (>2%). The following kinematic features are in line with previous studies: smaller knee flexion angular displacement (Yada et al., 2011), smaller knee extension angular displacement (Yada et al., 2011), greater hip extension velocity (Ae et al., 1992; Ito et al., 2008), smaller knee extension velocity (Ae et al., 1992; Ito et al., 2008), greater shank angular displacement (Alexander, 1989), and greater maximal leg backward swing velocity (Ae et al., 1992) during the support phase. For the kinematic variables related to the first half of the support phase, only the knee flexion angular displacement showed a large change (>2%) when running speed was increased. Just after foot strike, it is important to produce vertical force rapidly for high maximal speed sprinting (Clark and Weyand, 2014), and knee flexion during the first half of the support phase would suppress the production of the vertical force. Thus, the importance of producing vertical force rapidly during the initial support phase possibly explains the relationship between running speed and the knee flexion range. Greater relative toe-off distance, greater forward lean thigh and shank at toe-off, and greater hip, shank, and foot angular displacements during the support phase are all indicative of a more forward leaning leg position during the second half of the support phase. Although it is difficult to provide a clear rationale for the importance of these kinematic features for greater running speed, one possible reason is that a forward leaning leg posture is likely to facilitate the production of propulsive force (Kugler and Janshen, 2010), while this was determined during early acceleration and the importance of producing propulsive force disappears by the maximal speed phase (Nagahara et al., 2018a). As mentioned above, foot velocity in relation to the body center of mass is equal to running speed during the support phase, and the leg angular velocity is mechanically one of the determinants of this foot velocity, with

TABLE 3 | Multiple regression equations to calculate leg kinematic variables.

	Dependent variables [units]	Multiple regression equations	*p*	SEE	*R*	R^2
Swing leg kinematics	Thigh angle at contralateral foot strike [deg]	Y = 3.59·RS + 73.38·LL + 11.65·SF + 8.70·SSR – 172.25	<0.001	7.73	0.492	0.201
	Maximal thigh lift angle [deg]	Y = 4.57·RS + 2.07·LL – 6.20·SF – 2.45·SSR + 59.67	0.008	4.33	0.408	0.122
	Maximal knee flexion angular velocity [deg/s]	Y = −45.66·RS + 1165.12·LL – 96.13·SF + 40.61·SSR – 1364.41	<0.001	76.38	0.588	0.310
	Maximal thigh lift angular velocity [deg/s]	Y = 53.33·RS – 780.62·LL – 79.02·SF – 51.98·SSR + 1425.58	<0.001	41.85	0.485	0.194
	Maximal leg backward swing angular velocity [deg/s]	Y = −49.87·RS + 443.88·LL + 19.51·SF – 75.11·SSR – 184.86	<0.001	39.72	0.641	0.378
Support leg kinematics	Relative foot strike distance [%]	Y = 4.24·RS – 57.73·LL – 11.97·SF – 11.60·SSR + 146.43	<0.001	2.51	0.729	0.507
	Relative toe-off distance [%]	Y = 6.85·RS – 68.05·LL – 11.89·SF – 11.79·SSR + 151.84	<0.001	2.76	0.732	0.510
	Hip angle at foot strike [deg]	Y = −2.21·RS + 12.15·LL + 4.29·SF + 7.86·SSR + 99.31	0.002	3.39	0.450	0.159
	Knee angle at foot strike [deg]	Y = – 0.51·RS + 30.25·LL – 1.87·SF + 8.89·SSR + 113.24	0.005	5.21	0.422	0.134
	Ankle angle at foot strike [deg]	Y = 1.79·RS + 10.68·LL – 7.39·SF + 0.52·SSR + 129.15	0.014	4.11	0.391	0.107
	Hip angle at toe-off [deg]	Y = 5.50·RS – 75.78·LL – 9.98·SF – 7.76·SSR + 274.00	0.003	4.85	0.442	0.152
	Knee angle at toe-off [deg]	Y = 1.69·RS – 50.03·LL – 9.99·SF – 1.30·SSR + 229.36	0.037	4.62	0.357	0.080
	Ankle angle at toe-off [deg]	Y = 2.21·RS – 2.41·LL – 8.46·SF – 1.22·SSR + 170.17	0.046	4.36	0.348	0.074
	Knee flexion angular displacement [deg]	Y = −1.33·RS + 11.32·LL + 9.66·SF + 4.38·SSR – 68.00	<0.001	3.25	0.491	0.200
	Hip extension angular displacement [deg]	Y = 7.71·RS – 87.93·LL – 14.27·SF – 15.62·SSR + 174.69	<0.001	3.72	0.707	0.473
	Knee extension angular displacement [deg]	Y = 3.41·RS – 89.19·LL – 17.21·SF – 14.61·SSR + 181.06	<0.001	4.41	0.652	0.394
	Maximal hip extension velocity [deg/s]	Y = 100.74·RS – 1214.75·LL – 141.65·SF – 142.50·SSR + 1941.08	<0.001	61.95	0.568	0.286
	Maximal knee extension velocity [deg/s]	Y = 82.39·RS – 1970.14·LL – 340.27·SF – 296.98·SSR + 3732.32	<0.001	94.19	0.627	0.360
	Maximal ankle plantarflexion velocity [deg/s]	Y = 50.30·RS – 703.02·LL – 41.65·SF + 62.17·SSR + 1076.94	0.042	87.94	0.352	0.077
	Thigh angle at foot strike [deg]	Y = 2.18·RS – 37.32·LL – 4.89·SF – 10.76·SSR + 98.26	<0.001	2.82	0.640	0.378
	Shank angle at foot strike [deg]	Y = 1.67·RS – 7.07·LL – 6.75·SF – 1.87·SSR + 31.50	0.035	3.10	0.359	0.081
	Thigh angle at toe-off [deg]	Y = −4.02·RS + 64.31·LL + 10.12·SF + 7.17·SSR – 110.38	<0.001	3.04	0.557	0.273
	Shank angle at toe-off [deg]	Y = −2.33·RS + 14.28·LL + 0.13·SF + 5.87·SSR – 61.02	<0.001	2.57	0.517	0.228
	Foot angle at toe-off [deg]	Y = −4.54·RS + 16.69·LL + 8.60·SF + 7.08·SSR – 51.19	0.006	4.38	0.416	0.129
	Thigh angular displacement [deg]	Y = 6.20·RS – 101.63·LL – 15.01·SF – 17.92·SSR + 208.64	<0.001	3.25	0.785	0.595
	Shank angular displacement [deg]	Y = 4.00·RS – 21.35·LL – 6.89·SF – 7.73·SSR + 92.52	<0.001	3.18	0.507	0.217
	Foot angular displacement [deg]	Y = 4.42·RS – 34.44·LL – 7.96·SF – 9.46·SSR + 133.53	0.001	4.00	0.478	0.187
	Maximal leg backward swing angular velocity [deg/s]	Y = −61.31·RS + 853.19·LL – 16.52·SF – 4.39·SSR – 659.85	<0.001	21.23	0.877	0.757

RS, running speed [m/s]; LL, leg length [m]; SF, step frequency [Hz]; SSR, swing/support ratio; SEE, standard error of estimate; R, multiple correlation coefficient; R^2, determination coefficient adjusted for the degrees of freedom.

a greater hip extension velocity likely increasing this leg angular velocity. As knee extension would reduce the leg backward swing velocity during the support phase (Ito et al., 2008), increasing hip extension and suppressing knee extension velocities are again logical techniques for faster maximal speed sprinting through the role in facilitating higher leg backward swing velocity during the support phase.

The inter-individual differences in leg length (stature) have influence on leg kinematics for running at a specific speed (**Table 4**). When compared to the magnitudes of changes in kinematic variables in association with changes in running speed over ±2SD, corresponding magnitudes in association with changes in leg length over ±2SD were greater for 11 out of 21 variables. The fact that the difference in leg length has a comparable or greater influence on running kinematics in comparison with the differences in running speed demonstrates the importance of considering leg length for examining the kinematics of faster maximal speed sprinting. The knowledge gained in the current study is useful for considering the effects of differences in sprinters' leg lengths. Although there is no previous study against which a direct comparison can be made, Nagahara et al. (2018b) reported that greater stature was associated

TABLE 4 | Examples of changes in predicted leg kinematic variables for four conditions.

		Condition A			Condition B			Condition C			Condition D			Magnitude of change [%]			
		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(c)–(a)	(f)–(d)	(i)–(g)	(l)–(j)
Running speed [m/s]		**8.99**	**9.90**	**10.82**		9.90			9.90			9.90		**18.5**	0.0	0.0	0.0
Leg length [m]			0.812		**0.749**	**0.812**	**0.875**		0.812			0.812		0.0	**15.6**	0.0	0.0
Step frequency [Hz]		4.39	4.60	4.82	4.81	4.60	4.39	**4.27**	**4.60**	**4.94**		4.60		9.4	−9.1	**14.7**	0.0
Swing/support ratio		3.05	3.16	3.28	3.21	3.16	3.11	3.35	3.16	2.98	**2.74**	**3.16**	**3.59**	7.3	−3.2	−11.8	**26.9**
Swing leg kinematics	Thigh angle at contralateral foot strike [deg]	−2.8	4.1	10.9	2.3	4.1	5.8	1.7	4.1	6.4	0.4	4.1	7.8	335.4	86.2	114.9	181.7
	Maximal knee flexion angular velocity [deg/s]	−1,127	−1,185	−1,243	−1,277	−1,185	−1,093	−1,145	−1,185	−1,225	−1,202	−1,185	−1,167	9.8	−15.5	6.8	−2.9
	Maximal thigh lift angular velocity [deg/s]	766	792	817	822	792	761	809	792	774	814	792	770	6.5	−7.6	−4.3	−5.6
	Maximal leg backward swing velocity [deg/s]	−416	−466	−516	−494	−466	−438	−486	−466	−445	−434	−466	−498	21.5	−12.0	−8.8	13.7
Support leg kinematics	Relative foot strike distance [%]	49.8	49.8	49.8	50.3	49.8	49.2	51.7	49.8	47.9	54.7	49.8	44.9	−0.1	−2.2	−7.7	−19.8
	Relative toe-off distance [%]	70.0	72.4	74.7	73.6	72.4	71.2	74.2	72.4	70.6	77.4	72.4	67.4	6.5	−3.3	−5.1	−13.8
	Hip angle at foot strike [deg]	132.1	131.9	131.7	132.4	131.9	131.4	131.9	131.9	131.9	128.6	131.9	135.2	−0.3	−0.8	0.0	5.1
	Knee angle at foot strike [deg]	152.1	152.3	152.4	150.4	152.3	154.1	154.6	152.3	150.0	148.5	152.3	156.1	0.2	2.4	−3.0	5.0
	Hip angle at toe-off [deg]	194.4	196.4	198.4	198.7	196.4	194.1	198.4	196.4	194.5	199.7	196.4	193.1	2.0	−2.3	−2.0	−3.4
	Knee flexion angular displacement [deg]	−15.0	−13.6	−12.2	−12.1	−13.6	−15.2	−16.1	−13.6	−11.2	−15.5	−13.6	−11.8	−20.2	22.6	−36.2	−27.3
	Hip extension angular displacement [deg]	62.4	64.5	66.7	66.3	64.5	62.8	66.5	64.5	62.6	71.2	64.5	57.9	6.8	−5.5	−6.0	−20.6
	Knee extension angular displacement [deg]	19.2	16.9	14.6	18.2	16.9	15.6	20.1	16.9	13.8	23.1	16.9	10.7	−27.0	−15.2	−36.9	−73.3
	Maximal hip extension velocity [deg/s]	804	850	895	889	850	810	871	850	828	910	850	789	10.7	−9.4	−5.1	−14.3
	Maximal knee extension velocity [deg/s]	475	443	411	481	443	405	503	443	383	569	443	317	−14.6	−17.2	−27.2	−57.0
	Thigh angle at foot strike [deg]	33.3	33.0	32.7	33.8	33.0	32.3	32.7	33.0	33.4	37.6	33.0	28.5	−1.8	−4.8	2.1	−27.7
	Thigh angle at toe-off [deg]	−28.0	−28.7	−29.4	−30.3	−28.7	−27.1	−30.8	−28.7	−26.6	−31.8	−28.7	−25.7	4.7	−11.0	−14.6	−21.2
	Shank angle at toe-off [deg]	−51.9	−53.3	−54.8	−53.9	−53.3	−52.7	−52.3	−53.3	−54.4	−55.8	−53.3	−50.8	5.4	−2.2	3.9	−9.3
	Thigh angular displacement [deg]	61.4	61.8	62.1	64.1	61.8	59.4	63.5	61.8	60.0	69.4	61.8	54.1	1.2	−7.7	−5.7	−24.7
	Shank angular displacement [deg]	57.4	58.6	59.9	58.2	58.6	59.1	59.5	58.6	57.7	61.9	58.6	55.4	4.4	1.7	−3.1	−11.2
	Foot angular displacement [deg]	81.5	82.8	84.0	82.8	82.8	82.7	83.7	82.8	81.8	86.8	82.8	78.7	3.0	−0.1	−2.3	−9.7
	Maximal leg backward swing angular velocity [deg/s]	−604	−664	−724	−722	−664	−606	−659	−664	−669	−662	−664	−666	18.2	−17.4	1.4	0.6

*Condition A: Predicted kinematic variables when the sprinter's leg length was 0.812 m (mean value in this study) and running speeds were 8.99, 9.90, and 10.82 m/s (mean ± 2SD values in this study). The values of step frequency were calculated using the regression equation presented in **Table 2** with running speeds and leg length, while the values of the swing/support ratio were computed using the regression equation presented in **Table 2** with running speeds, leg length, and predicted step frequencies.*

*Condition B: Predicted kinematic variables when running speed was 9.90 m/s (mean value in this study) and the sprinter's leg lengths were 0.749, 0.812, and 0.875 m (mean ± 2SD values in this study). The values of step frequency were calculated using the regression equation presented in **Table 2** with running speed and leg lengths, while the values of the swing/support ratio were computed using the regression equation presented in **Table 2** with running speed, leg lengths, and predicted step frequencies.*

*Condition C: Predicted kinematic variables when running speed was 9.90 m/s, the sprinter's leg length was 0.812, and step frequencies were 4.27, 4.60, and 4.94 Hz (mean ± 2SEE values in this study). The values of the swing/support ratio were computed using the regression equation presented in **Table 2** with running speed, leg length, and step frequencies.*

Condition D: Predicted kinematic variables when running speed was 9.90 m/s, the sprinter's leg length was 0.812, step frequency was 4.60 Hz, and swing/support ratio were 2.74, 3.16, and 3.59 (mean ± 2SEE values in this study).

Bold numbers indicate manipulated predictor variables.

with lower step frequency and longer support time during the maximal speed sprinting, thus partially supporting the current findings. Based on the obtained regression equations with major kinematic changes, longer-legged sprinters will accomplish the same running speed with a lower step frequency, a greater thigh angle at contralateral foot strike, smaller maximal knee flexion velocity during the swing phase, smaller leg backward swing velocities during the swing and support phases, greater flexion and smaller extension ranges of knee joint during the support phase, and smaller thigh forward lean at toe-off.

At a given running speed and leg length, based on the obtained regression equations with major kinematic changes, higher step frequencies will be achieved with a lower swing/support ratio, a greater thigh angle at contralateral foot strike, smaller knee flexion and extension ranges during the support phase, smaller maximal knee extension velocity, and smaller thigh forward lean angle at toe-off (**Table 4**). Trying to recover the swing leg earlier and to suppress changes in knee joint angle during the support phase therefore may result in increases in step frequency. At a given running speed, leg length, and step frequency, based on the obtained regression equations with major kinematic changes, a greater swing/support ratio will be accomplished with a greater thigh angle at contralateral foot strike, smaller hip extension, knee flexion and extension ranges during the support phase, smaller maximal knee extension velocity during the support phase, smaller thigh angles at foot strike and toe-off (both close to the upright position), and smaller thigh angular displacement during the support phase (**Table 4**). Trying to recover the swing leg earlier and to suppress changes in knee joint angle with a small range of thigh motion during the support phase will therefore raise the swing/support ratio.

Using running speed, leg length, and spatiotemporal variables which can be collected using smartphone in addition to the regression equations obtained in this study, a model of leg kinematics during the maximal speed sprinting can be provided. Although angular velocities are difficult to obtain for practitioners, joint angles can be measured using freely-available software (e.g., Kinovea) to analyse images from an appropriately positioned video camera. This will make it possible to compare the model leg kinematic features for specific running speed with the current kinematic features of a sprinter. Consequently, the regression equations in this study will be useful for sprinters and coaches when trying to improve leg kinematics for achieving higher maximal running speed.

Regarding the limitations of the current study, the participants employed in this study ranged from 10.30 to 12.14 s. Thus, the obtained regression equations are appropriate for the range of sprinters' performance level used in this study, and it is possible that the results might differ when sprinters with smaller range of performance levels are employed. Because we did not use multiple cameras to obtain three dimensional coordinates of body segments, influences of running speed, leg length, and spatiotemporal variables on leg kinematics in the coronal and transverse planes during maximal speed sprinting are still unknown. As the locations of the body landmarks were manually digitized and the foot strike and toe-off instants were visually detected, an investigation using a motion capture system which consists of infra-red cameras and force platforms will possibly derive different results compared to the current results. There was a variation of adjusted R^2 values among multiple regression equations, and this indicates that there would be other variables which have influences on the kinematics of maximal speed sprinting. For some variables, even if there was a medium effect size (adjusted $R^2 > 0.13$), the adjusted R^2 value indicates that the multiple regression equation can partially (>13%) explain the changes in a kinematic variable. Because this was a cross-sectional study as the regression equations were extracted using data from 79 sprinters, it is possible that intra-individual changes in kinematic variables associated with changes in running speed, step frequency, and swing/support ratio are not consistent to the predicted changes using the multiple regression equations. Although we instructed participants to achieve their maximal speed during the section from the 40- to 50-m mark, it is possible that the exact maximal sprint speed was not appeared within the section from 40 to 50-m mark for some participants because we did not measure consecutive running speed from the start of the trial. However, the running speed and modality only slightly changes around the maximal speed in sprinting (Nagahara et al., 2014a; Slawinski et al., 2017), and thus it can be considered that the influence of difference in locations of maximal speeds is negligible as previous studies adopted the same locations for investigating kinematics and kinetics of maximal speed sprinting (Alexander, 1989; Bushnell and Hunter, 2007; Bezodis et al., 2008; Yada et al., 2011). Although this study was performed with male sprinters, Ciacci et al. (2017) clarified that kinematics of sprinting was only partially affected by the sex of sprinters, and the differences in kinematics were mainly produced by the difference in performance level. Therefore, there is the possibility that the findings in this study may translate to female sprinters as long as they are within the studied performance levels.

In conclusion, employing a large number ($n = 79$) of sprinters over a relatively wide range of performance levels (10.30–12.14 s), multiple regression equations taking into account differences in running speed, leg length, and step characteristics to predict kinematics of maximal speed sprinting were successfully obtained, and leg kinematic features of faster maximal speed sprinting at different leg length and step characteristics were elucidated using the regression equations. The regression equations obtained in this study will be useful for sprinters and coaches when trying to improve their maximal speed sprinting motion based on the specific target changes in running speed and spatiotemporal variables for individuals with different leg lengths.

DATA AVAILABILITY STATEMENT

The datasets generated for this study will be made available by the authors, after explicit and justified request, to any qualified researcher.

ETHICS STATEMENT

This studies involving human participants were reviewed and approved by Research ethics committee of the Faculty of Health and Sports Sciences, University of Tsukuba (#22-409). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

KM, RN, KY, and TN contributed to conceiving, designing, performing the experiment, analyzing the data, drafting, and revising the article. KM performed most of the data analysis. RN performed most of drafting the article.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2019.00037/full#supplementary-material

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REVIEW
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"Question Your Categories": the Misunderstood Complexity of Middle-Distance Running Profiles With Implications for Research Methods and Application

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Middle-distance running provides unique complexity where very different physiological and structural/mechanical profiles may achieve similar elite performances. Training and improving the key determinants of performance and applying interventions to athletes within the middle-distance event group are probably much more divergent than many practitioners and researchers appreciate. The addition of maximal sprint speed and other anaerobic and biomechanical based parameters, alongside more commonly captured aerobic characteristics, shows promise to enhance our understanding and analysis within the complexities of middle-distance sport science. For coaches, athlete diversity presents daily training programming challenges in order to best individualize a given stimulus according to the athletes profile and avoid "non-responder" outcomes. It is from this decision making part of the coaching process, that we target this mini-review. First we ask researchers to "question their categories" concerning middle-distance event groupings. Historically broad classifications have been used [from 800 m (∼1.5 min) all the way to 5,000 m (∼13–15 min)]. Here within we show compelling rationale from physiological and event demand perspectives for narrowing middle-distance to 800 and 1,500 m alone (1.5–5 min duration), considering the diversity of bioenergetics and mechanical constraints within these events. Additionally, we provide elite athlete data showing the large diversity of 800 and 1,500 m athlete profiles, a critical element that is often overlooked in middle-distance research design. Finally, we offer practical recommendations on how researchers, practitioners, and coaches can advance training study designs, scientific interventions, and analysis on middle-distance athletes/participants to provide information for individualized decision making trackside and more favorable and informative study outcomes.

Keywords: anaerobic speed reserve, training science, fiber type, individualized training, coaching, bioenergetics

INTRODUCTION

In the book *Factfulness* the late Professor Hans Rosling addresses "Ten reasons why we're wrong about the world" (Rosling et al., 2018). Specifically, Rosling explains how we subconsciously employ bias in our decision making and interpretation of the world based on self-narrative, which can drive false positive and negative understanding of reality. Accordingly, we will apply one of Professor Rosling's ten-principles: *"Question your categories"* to an approach generally employed by many middle-distance researchers; in that, generally, many take a singular approach to the treatment and analysis of middle-distance athletes and/or study participants. Biological first principles consistently demonstrate a huge variability in adaptation to a given exercise stimulus and is prevalent across multiple sports (Gaskill et al., 1999; Vollaard et al., 2009; Timmons et al., 2010; Sylta et al., 2016). Therefore, a "one-size-fits-all" approach needs re-consideration based on substantial individual responses to a given stimulus, that is especially unique to the middle-distance event group resulting in very different physiological and mechanical profiles achieving similar elite performances (Schumacher and Mueller, 2002; Sandford et al., 2019a). Many in the middle-distance coaching community already generally implement individualized training (Horwill, 1980; Daniels, 2005), but highlight the need for deeper information surrounding how to best address the complexity of middle-distance athletes. It is from this coaching perspective that we target this mini-review, providing recommendations on how researchers/practitioners can advance training study designs, scientific interventions, and analysis in middle-distance athlete profiles research to provide more beneficial information for individualized decision making and/or more favorable and informative study outcomes.

WHAT CONSTITUTES MIDDLE-DISTANCE?

Consistency of both sport science terminology (Chamari and Padulo, 2015; Winter et al., 2016) and grouping of middle-distance events and athletes within the literature is lacking. Therefore, initially, we put forward a framework for defining middle-distance running events as *solely* the 800 and 1,500 m events (∼1.5 to 5 min duration; **Table 1**); primarily due to the demarcation of average 800 and 1,500 m race pace intensity in relation to a given physiological threshold (beyond VO_2max; **Table 1**).

The distinction of middle-distance as solely 800 and 1,500 m is critical for advancing current understanding. First, between 0 and 5 min, performance decrements of all-out efforts are exponential as a function of time (Bundle and Weyand, 2012). Therefore, within this time frame, a varying blend, but still large contributions, of (1) aerobic, (2) anaerobic, and (3) neuromuscular/mechanical characteristics are implemented to achieve optimal performance (Schumacher and Mueller, 2002; Sandford et al., 2019a). An appreciation of the differences in these three distinct performance determinants between, and within, middle-distance events has received limited consideration within the middle-distance literature, largely perhaps due to our limitations in accurately and reliably quantifying anaerobic energetics (Haugen et al., 2018). If one extends the middle-distance category beyond ∼5 min (for example to 7,8, or 15 min) a much smaller decline in performance is seen (between e.g., 5 and 9 min than between 1 and 5), due to the similar nature of aerobic contribution support the extended duration (e.g., 5–9 min) of exercise (Bundle and Weyand, 2012; **Table 1**). Second, the average race pace of 800–1,500 m as a % VO_2max, are beyond VO_2max, providing distinctly different metabolic consequences to those events that are below VO_2max, both of which are distinctly different to those events that reside, on average, below critical velocity (defined as the last wholly oxidative physiological intensity; **Table 1**). Therefore, it is important that in establishing middle-distance event specific performance determinants, and/or appropriate performance enhancing interventions, that the bioenergetics and neuromuscular/mechanical requirements represent the actual demands from ∼1.5 to 5 min of duration, which are much different if one includes middle to long and long distance athletes (**Table 1**).

Consequently, training and applying interventions to athletes within this middle-distance event group are much more divergent than many practitioners and researchers appreciate. Indeed, recent work in elite 800 m runners has shown huge diversity of profiles presenting along the continuum of middle-distance running (Sandford et al., 2019a), which we will discuss below. Accordingly, we suggest that given the unique bioenergetics (**Table 1**) and neuromuscular/mechanical constraints, that middle-distance are exclusively defined as the 800 and 1,500 m athletics events, or ∼1.5 to 5 min of duration.

MIDDLE-DISTANCE RUNNING—THE EVENT GROUP WITH LARGEST DIVERSITY OF ATHLETE PROFILE?

The middle-distance events are described as the "middle-ground" of aerobic and anaerobic energetics (Billat, 2001; **Table 1**), where, accordingly, athletes may approach the same performance time from distinctly different perspectives, as shown by diversity of aerobic energetics within the 800 m (**Table 1**). Indeed, most coaches appreciate the large variability of aerobic energetics across the 800 m event when programming training (Gamboa et al., 1996), which actually aligns well with the published diversity of energetic contributions (**Table 1**). As an example, published case studies on world-class 1,500 m runners Henrik Ingebrigtsen (Tjelta, 2013) and Peter Snell (Carter et al., 1967) show substantial diversity in physiology (VO_2max) and performance profile at 800 and 3,000 m, despite similar 1,500 m race performances (3:35.43 and 3:37.60, respectively, at time of publication). For example Ingebrigtsen presents with a VO_2max of 84.4 vs. Snell's value of 72.2 ml/kg/min. Ingebrigtsen's personal best at 800 and 3,000 m are 1:48.60 and 7:58.15, respectively. By comparison, over the 800 m Snell recorded 1:44.30 world-record and had no recorded 3,000 m race performances (but did record 9:16 on grass and 9:12.5 on cinder tracks over 2 miles (*Steve Willis personal communication*), which converts to 8:36.10 and 8:32.90 3,000 m (IAAF scoring tables). Therefore,

TABLE 1 | Proposed framework for standardizing researcher and practitioner categories of events 800 m—marathon considering both average race velocity and subsequent physiological consequences of a given race demand.

Parameter	Middle-distance		Middle-long distance			Long distance	
Events	**800 m (min:ss:ms)**	**1,500 m (min:ss:ms)**	**3,000 m (min:ss:ms)**	**5,000 m (min:ss:ms)**	**10, 000 m (min:ss:ms)**	**60 min record (~l/2 marathon) (min:ss)**	**Marathon (hr:min:ss)**
Male world record event duration (hr:min:ss:ms)	1:40.91	3:26.00	7:20.67	12:37.35	26:17.53	58.18	2:01:39
Average race pace intensity (% VO_2max; Billat, 2001)	115–130	105–115	~100	95–100	90–95	85–90	75–80
Physiological threshold	Above VO_2max		$\leq VO_2$max, $\geq$ Critical velocity			<Critical velocity	
% Aerobic energy contribution (Billat, 2001)	65–75	80–85	85–90	90–95	97	98	99.9
% Aerobic energy contribution (Spencer and Gastin, 2001)	66 ± 4	84 ± 3	n/a	n/a	n/a	n/a	n/a
% Aerobic energy contribution (Duffield et al., 2005a,b)	60.3 ± 9	77 ± 7	86 ± 7	n/a	n/a	n/a	n/a
Coach interpretation of % aerobic energy contribution (Gamboa et al., 1996)	35–65	n/a	n/a	n/a	n/a	n/a	n/a
% difference in aerobic contribution to 800 m	–	5–20	10–25	20–30	22–32	23–33	24.9–34.9

Adapted from Gamboa et al. (1996), Billat (2001), Spencer and Gastin (2001), Duffield and Dawson (2003), Duffield et al. (2005a,b).

despite these two athletes having similar 1,500 m race times, it is obvious that Snell's 1,500 m performance comes much more from a speed/anaerobic physiological profile compared to the more aerobic profile from Ingebrigtsen. In further support of divergent middle-distance athlete profiles, a recent global sample by Sandford et al. (2019a) revealed substantial diversity of athlete profile within elite male 800 m athletes, that can be categorized by three distinct sub-groups (400–800 m speed types, 800 m specialists and 800–1,500 m endurance types) across a continuum (**Figure 1A**). The same within 800 m subgroups are also found in elite females (**Figure 1B**; where velocity at 4 mmol (v4mmol) has also been added). Providing just three measures of an athletes profile, such as v4mmol (aerobic indicator), velocity at VO_2max (vVO_2max; aerobic power indicator) and maximal sprinting speed (MSS; biomechanical/structural indicator, measured over 50 m from standing start, Sandford et al., 2019a) provides a great "first layer insight" for any researcher, practitioner, and coach. From this, one can more easily identify: (a) the physiological and biomechanical strengths and limitations of an individual; and (b) which "sub-group" the athlete/participant is currently in. This, in turn, potentially enables more targeted interventions by sub-group to improve depth of understanding on stimulus-response of interventions across the middle-distance continuum which ultimately aid the ability to inform individualized training prescription.

It is important to note, that without the characterization of MSS in these middle-distance athletes, something which is rarely reported in middle-distance studies, this continuum characterization is not possible (**Figures 1A,B**). Interestingly, these identified middle-distance athlete sub-groups (Sandford et al., 2019a) supports longstanding coaching observations of middle-distance athlete variability that requires careful individual considerations (Horwill, 1980).

We suggest that appreciating the continuum of middle-distance diversity is currently poorly implemented in many research study designs, and poorly appreciated amongst middle-distance researchers and practitioners. Accordingly, as outlined below and in **Table 2**, considerations of this diversity should occur with: (l) section Study Athlete/Participant Characterization and Description (II) section Selection of Appropriate Intervention - Are All Stimulus Created Equal?; and (III) section Analysis of Effects per Sub-group.

Study Athlete/Participant Characterization and Description

All studies are required to profile and characterize their participants (Begg et al., 1996). Typically, many middle-distance based studies tend to limit this reporting to primarily aerobic based physiological parameters, such as VO_2max (or vVO_2max), lactate threshold, and performance times and participant age and anthropometrics. Sometimes, depending on the scope of the study, some anaerobic metrics are provided, appreciating sport science currently has limited validity in accurately and sensitively measuring the anaerobic domain (Haugen et al., 2018). Furthermore, middle-distance coaching education is predominated by aerobic based energy system teaching (Berg, 2003; Thompson, 2016; Sandford, 2018), which may skew the over-emphasis on these performance elements.

In Rosling's words we should look to "get-a tool box not a hammer." Accordingly, we suggest that neuromuscular and mechanical qualities, such as MSS and the anaerobic speed reserve (ASR, defined as the speed range from Velocity at VO_2max to MSS, Blondel et al., 2001; Buchheit and Laursen, 2013), offer potential to deepen our understanding of athlete profile diversity. At the very least, the addition of MSS allows for enhanced potential analysis (see **Figures 1A,B**), and is a technically and methodologically easy addition to most study designs. However, very rarely, are any maximal speed/power and/or biomechanics based metrics reported or considered (despite considerable evidence showing them to be important performance determinants of MSS Weyand et al., 2000, 2010; Morin et al., 2011; Rabita et al., 2015; Nagahara et al., 2019) as well as determinants of middle-distance race performance (Nummela et al., 1996; Bachero-Mena et al., 2017; Sandford et al., 2019a).

Furthermore, many papers only report single event performance, which does not inform the reader on where

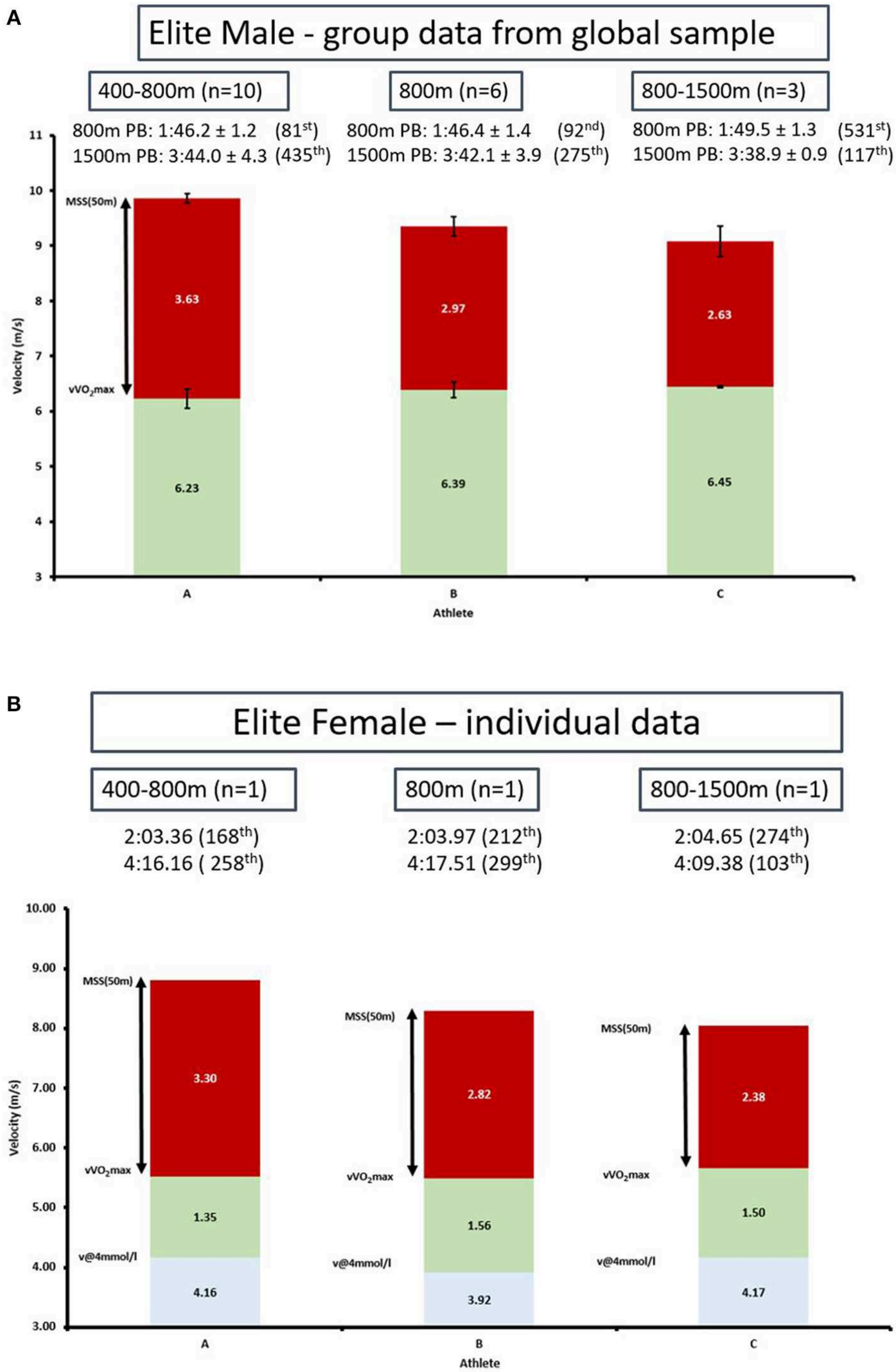

FIGURE 1 | (A) Anaerobic speed reserve profiles of 19 elite male 800 and 1,500 m athletes across 800 m sub-group continuum as described in Sandford et al. (2019a). All participants seasons best (SB) 800 m ≤1:47.50 and 1,500 m SB ≤3:40.00. vVO_2max estimated from 1,500 m race time as per methods of Bellenger et al. (2015) and validated in elite male runners in Sandford et al. (2019b). **(B)** Anaerobic speed reserve and velocity at 4 mmol/l lactate (v@4 mmol/l) across three elite middle-distance female profiles from each of the 800 m sub-groups tested in 2017. Note the between individual diversity across v@4 mmol/l, vVO_2max and Maximal sprint speed—despite all having a season's best over 800 m within 1.3 s of each other. Rankings in brackets from 2017 season. vVO_2max generated using methods developed by Bellenger et al. (2015) and utilized in Sandford et al. (2019a) **(A)**. Informed consent was obtained through Auckland University of Technology ethics committee as part of Sandford et al. (2019a).

the strengths and weaknesses of a given athletes/participants lie (e.g., **Figures 1A,B**). Athlete/participant profiles may be further characterized by concepts such as ASR and the speed reserve ratio (SRR; MSS/vVO_2max) allowing authors to describe the distribution of their athlete/participants sub-group(s). As a minimum authors should show a spread of performance times,

TABLE 2 | Study design principles for middle-distance running populations.

Example Research Question: "The effect of high intensity training interventions at or beyond VO_2max on middle-distance race performance"				
	Traditional approach	**Issues with approach**	**Emerging approaches**	**Rationale**
 I. Participant description	"18 middle-distance runners," height, weight, age, international ranking level, VO_2max, middle-distance performance times	Does not provide enough information to distinguish what type of middle-distance athlete the participants since MSS is not assessed	MSS measured over 50 m used to complement the aerobic characterization of vVO_2max. Elite Athletes presented across the middle distance continuum, $n = 400–800$, $n = 800$, and $n = 800–1,500$ and categorized using the SRR (MSS/vVO_2max) (Sandford et al., 2019a) Performance times provided across multiple distances (400, 800, 1,500) Training volume, time in zones quantified to understand training history	Allows for sub-group characterization even in underpowered studies that can have closer application and relevance for coaches and support staff frontline or for future study hypothesis generation
II. Exercise prescription	%vVO_2max (>VO_2max) %HRmax (>VO_2max) Event personal best running speeds (e.g., intervals at 800 or 1,500 m race pace)	Human locomotor performance (i.e., time to exhaustion) at intensities beyond vVO_2max can be surprisingly "predicted" using only 2 locomotor entities: vVO_2max and MSS (Bundle et al., 2003; Alexander, 2006; Bundle and Weyand, 2012) Therefore, without acknowledgment of the MSS differences, the intervention will have athletes working at different relative intensities of a given workload. For example, the lower the use of the ASR, the greater the exercise tolerance (Blondel et al., 2001; Buchheit et al., 2012; Buchheit and Laursen, 2013) and thus a big confounder often overlooked in these types of studies	% ASR (or exercise prescription decisions set relative to both %vVO_2max and %MSS)	Accounts for mechanical differences between athletes and allows the same relative physiological stimulus to be applied (Buchheit and Laursen, 2013)
III. Analysis	(1) All runners grouped together for analysis (despite some studies having 800 m (1.5–2 min) to marathon (130–160 min) specialists. (2) Periodically a sub-group responders vs. non responders	Misrepresentation of athletes ability to "respond." Should we expect all athletes to respond equally to the same stimulus despite having very different event specialty or diverse profile to approach the same event?	Analyze data as a single group, BUT also display individual and sub-group response and differences between subgroups	Further understanding the appropriateness of a stimulus for a given sub-group profile

for example 400, 800, and 1,500 m personal bests. Expanding upon the athlete/participant profile in a study design allows for significant improvement in analysis as well as for applied sport practitioners and coaches to determine the relevance of study findings to the athletes they coach.

Selection of Appropriate Intervention—Are All Stimulus Created Equal?

Many papers report responder or-non-responder outcomes following a blanket intervention without inspection of participant profile diversity (see: Gaskill et al., 1999; Vollaard et al., 2009; Timmons et al., 2010; Sylta et al., 2016). This may result in assuming a "non-response." Conversely, perhaps an inappropriate stimulus was implemented for their unique sub-group profile that has created the "non-responder" outcome, rather than the athlete's inability to adapt. Equally, the same stimulus may have favored other uniquely identified subgroups in the sample resulting in responders. Such scenarios are daily challenges in coaching and an area where furthering our scientific approach could add great resolution to inform frontline decision making. Interestingly, a recent paper highlighting the value of an individualized training intervention, albeit in a team sport group by Jiménez-Reyes et al. (2017) demonstrate that individualized programming based on a subjects baseline force-velocity profile led to greater improvements in jump performance, with less variability, compared to a generic non-individualized strength training programme.

One major mechanism (but not exclusive from other neural and morphological components) underpinning the diversity of middle-distance athletes and unique adaptive profiles might be muscle fiber typing. Slow twitch muscle are characterized by myosin heavy chains (MHC) I and fast twitch by MHC II [sum total of MHC lla (fast oxidative) and IIx (fast glycolytic)], and shall be discussed using these isoforms herein. Historical understanding of fiber typing at the extremes of speed and endurance have been well-understood since the 1970s (Costill et al., 1976), but the blend of these qualities in the middle-distance are less clear (van der Zwaard et al., 2017). MHC IIa and IIx fiber composition is a common characteristic underpinning elite speed and power performance. For instance, a former world champion sprint hurdler demonstrated an impressive 71% MHC II (24%llx) (Trappe et al., 2015). MHC II also has a superior ability to hypertrophy (Billeter et al., 2003). Further characteristics of MHC II muscle include larger baseline muscle carnosine content (Parkhouse et al., 1985; Baguet et al., 2011) that have been related to frequency of movement (i.e., more MHC II, higher frequency of movement) (Bex et al., 2017); and enhanced muscle buffering. In addition, greater creatine content is also found at rest in MHC II muscle, which supports more anaerobic based exercise (Tesch et al., 1989). All of these facets have implications for muscle buffering capacity, sensitivity to supplementation and intervention designs with ergogenic aids (Stellingwerff et al., 2019).

By contrast distance runners (5 km–to marathon) have shown a MHC I fiber range of 63.4 to 73.8%, with 1972 Olympic Marathon gold-medalist Frank Shorter having 80% MHC I (Costill et al., 1976). Taken together, differences in fiber typing and specific hypertrophy, highlights the complexity of any one type of stimulus to a phenotypic adaptive outcomes that requires careful future sub-group investigation.

In the middle of this MHC I-to-MHC II continuum lie the middle-distance athletes (Costill et al., 1976; Baguet et al., 2011). The concurrent event demand for middle-distance athletes of speed and endurance is at conflict with the inverse relationship between oxidative capacity and muscle cross sectional area (CSA—where MHC II are larger), alongside the strong relationship between MHC I and oxidative enzyme activity (Zierath and Hawley, 2004; van der Zwaard et al., 2016). Therefore, a given middle-distance athlete may present from varying points along this fiber-type continuum. For example, Costill et al. (1976) revealed a large MHC I range of 44.0–73.3% and 40.5–69.4% in female and male middle-distance runners, respectively. Interestingly, these fiber type ranges overlaps with the aerobic contribution to the 800 and 1,500 m events (**Table 1**).

Without separating the presenting diversity into sub-groups in our study designs, we are potentially blurring the individuality of responses that may be present, and thus, perhaps losing effects that work for some sub-groups and not others. An alternative may be to consider what interventions may be appropriate for a given sub-group within a study population, rather than applying a generic intervention to all participants; much like a coach does daily in prescribing training for their athletes.

Analysis of Effects per Sub-group

The consequence of employing blanket interventions to one group is the "signal" of the effect may be lost in the diversity of the athlete sample, which presents as non-significant "noise." Therefore, approaches such as ASR, alongside measures of critical velocity/v4mmol/l, can allow for significantly enhanced data analysis. In the end, it is best to not choose one model, but a broad perspective (multidisciplinary approach) to fully develop the athlete profile and subsequent analysis. In addition consideration of mechanical differences such as aerial or terrestrial profiles (Lussiana and Gindre, 2016) or baseline muscle carnosine (Baguet et al., 2011), representative of fiber-typing could add huge value in characterizing and determining effective interventions for the different sub-groups. Given some research interventions will have more relevant categories than others (e.g., aerial vs. terrestrial biomechanics vs. ASR sub-group using SRR vs. baseline muscle carnosine/creatine), consider presenting results using multiple layered sub-groups (e.g., 400–800 m athlete aerial profile vs. 400–800 m terrestrial profile), to potentially provide a more complete understanding of the complex characteristics between and within middle-distance athletes. Finally, the smallest worthwhile change to competitive performance in elite—middle-distance running (defined as <3 km) is 0.5% (Hopkins, 2005). Bringing to question whether our investigations and groupings of 800–5,000 m as "middle-distance," with up to 30% difference in aerobic energetic demands (**Table 1**) are too broad to determine an effect that matters to performance within the sub-group complexity.

CONCLUSION AND RECOMMENDATIONS

In the present mini-review we, first, provide a call to action for authors to *"Question your categories"* with regards to broad unidimensional classification of the middle-distance running events. Second, we outline multiple areas at an athlete/participant level where research design and consideration for sub-group outcomes at multiple steps (section Study Athlete/Participant Characterization and Description, Selection of Appropriate Intervention—Are All Stimulus Created Equal?, Analysis of Effects Per Sub-group; **Table 2**) can enhance the application of research to the coach and practitioner frontline. Until the inherent diversity of athlete profiles are appreciated by the middle-distance research and practitioner community, many current generic middle-distance sport science recommendations and associated research methods will continue to provide a misleading narrative and understanding of effective middle-distance interventions. It is for sport scientists at the frontline to connect the sub-group understanding and characterization from the lab to the track, enabling our coaches to make the most informed recommendations about individualizing interventions based on the athlete presenting in front of them.

To conclude, in the words of Professor Hans Rosling *"It will be helpful to you if you always assume your categories are misleading. Here are five powerful ways to keep questioning your favorite categories: look for differences within and similarities across groups; beware of the majority; beware of exceptional examples; assume you are not normal; and beware of generalizing from one group to another."*

It is from this paradigm that we believe more progress will be made in understanding the complexities, and training stimulus approaches in applied sport science application to middle-distance running.

AUTHOR CONTRIBUTIONS

GS and TS were involved in the conceptual ideas, writing a first draft of the paper, selection and production of figures and tables, and revising the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Translating Science Into Practice: The Perspective of the Doha 2019 IAAF World Championships in the Heat

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Hot and humid ambient conditions may play a major role during the endurance events of the 2019 IAAF world championships, the 2020 summer Olympics and many other sports events. Here, various countermeasures with scientific evidence are put in perspective of their practical application. This manuscript is not a comprehensive review, but rather a set of applied recommendations built upon sound scientific reasoning and experience with elite athletes. The primary recommendation for an athlete who will be competing in the heat, will be to train in the heat. This acclimatization phase should last for 2 weeks and be programmed to accommodate the taper and travel requirements. Despite extensive laboratory-based research, hydration strategies within athletics are generally dictated by the race characteristics. The main opportunities for hydration are during the preparation and recovery phases. In competition, depending on thirst, feeling, and energy requirements, water may be ingested or poured. The athletes should also adapt their warm-up routines to the environmental conditions, as it may do more harm than good. Avoiding harm includes limiting unnecessary heat exposure before the event, warming-up with cooling aids such as ice-vest or cold/iced drinks, and avoiding clothing or accessories limiting sweat evaporation. From a medical perspective, exertional heat stroke should be considered immediately when an athlete collapses or struggles during exercise in the heat with central nervous system disorders. Once a rectal temperature >40.5°C is confirmed, cooling (via cold water immersion) should be undertaken as soon as possible (cool first/transport second).

Keywords: heat acclimatization, hydration, acclimation, pre-cooling, exertional heat illness

INTRODUCTION

The 17th IAAF World Championships will take place in Doha, from the 27th September to the 6th October 2019. While the track and field events will be held in an AC stadium, the road races will be held on the seaside, at night time. A retrospective analysis of 36-years of MERRA-2 meteorological data over the competition period indicates that weather conditions are typically both hot and humid during this time of the year, with average maximum daytime temperatures reaching 38°C, and average daily dewpoint temperatures approaching 22°C. The temperature peaks early afternoon (range 33–42°C) and is the lowest at night (range 23–31°C). The WBGT follows a similar pattern with a mid-day peak (average 33°C, range 27–44°C) and an overnight minimum (average 24°C, range 19–28°C). Such conditions impair endurance performance and increase the risk of exertional heat illness (Racinais et al., 2015a). As such, understanding the mitigating factors surrounding human thermoregulation, knowledge, and practice of effective countermeasure strategies and medical care are imperative to ensure adequate and safe athlete preparation and performance (Alhadad et al., 2019). This manuscript briefly puts in perspective the main countermeasures to mitigate heat stress considering their scientific evidence as well as their practicability during the athletic championship.

TRAINING IN THE HEAT: FAILING TO PLAN IS PLANNING TO FAIL

Heat stress has been shown to dramatically decrease endurance performance, but this decrement can be progressively attenuated with the acclimatization induced by repeated training in the heat (Racinais et al., 2015b). Importantly, heat acclimatization may also reduce the likelihood of suffering from heat illnesses. As such, heat acclimatization should be a priority before any event where the ambient conditions may be hot and/or humid, even if the level of heat stress may be mild or uncertain. Indeed, heat acclimatization does not impair performance in cooler environments and may even improve it under some circumstances (Lorenzo et al., 2010; Racinais et al., 2014). Briefly, the most visible adaptations of the body to repeated training in the heat include an increased sweat rate, a decreased heart rate at a given intensity, a better retention of electrolytes, and a decreased body core temperature (**Figure 1**; Périard et al., 2015; Tyler et al., 2016; Daanen et al., 2018).

Intuitively, it can be reasoned that the most specific adaptations would be conferred by training in the same environment as the upcoming competition. However, where such an undertaking may not be possible, the use of artificial heat exposure such as training in a hot room, sauna bathing, hot bath post thermoneutral training are potentially some useful alternatives (**Figure 2**). The fundamental requisite for an effective heat acclimation involves substantial and repeated increases in core temperature, skin temperature, and sweating. In addition, the relative success of a heat adaptation program depends on the specificity (active vs. passive) and frequency of the exposure. It is ideal that at least 60–90 min of exercise is undertaken in the heat to confer rapid adaptations (Tyler et al., 2016), and a total period of 2 weeks is allocated to facilitate maximal adaptations (Racinais et al., 2015b). Additional training sessions may be done in cooler environments, whilst it is recommended that sleep and recovery should always be in a cool environment. When training in the heat, the relative intensity can be controlled by heart rate throughout acclimation (Périard et al., 2015). A decrease in absolute training intensity is usually evident during the initial days of heat acclimation, and it is possible to commence the acclimation program at reduced thermal load (i.e., lower environmental temperatures, exercise duration or intensity). If training in the heat includes high-intensity workouts with a neuromuscular focus, this should be done at the beginning of the session, before athletes attain elevated body temperatures (Karlsen et al., 2015b).

The time required to achieve optimal acclimatization may vary but most adaptations have been shown to develop within 7–10 days, with 14 days being preferable (Karlsen et al., 2015a; Périard et al., 2015; Racinais et al., 2015b; Tyler et al., 2016). It is thus generally recommended that 2 weeks of heat acclimation be undertaken prior to competing in hot and/or humid ambient conditions (Racinais et al., 2015a). Adaptations gathered following heat acclimation have been shown to decay in a symmetrical fashion, but with probably a slower pace. Indeed, most adaptations have been shown to decline following 1–2 weeks, but some benefits can be maintained for up to 1 month (Daanen et al., 2018). The rate of decay can be prolonged by including heat exposures post-acclimation/acclimatization. Importantly, re-acclimation following a dedicated period of heat-acclimation has been shown to be more accelerated compared with the initial rate of acclimation (Weller et al., 2007). Thus, conducting an initial heat acclimatization camp several weeks before the target event may increase the speed at which adaptations occurs in a follow-up pre-competition camp. For example, the main acclimatization block can be performed in the 2 weeks prior to travel, with 4–5 days of re-acclimation after arrival at the competition venue. Such planning accounts for the tapering need of the athlete before a major competition (Daanen et al., 2018). Thus, it may be more feasible if an acclimatization block was to be undertaken a few weeks before, followed by acute heat exposure throughout the taper to maintain the initially conferred adaptations. It is also possible to incorporate passive heat acclimation techniques such as sauna bathing (Scoon et al., 2007) and hot water immersion (Zurawlew et al., 2016) for 30–40 min pre- or post-training. This approach takes advantage of core temperature being elevated from training and can be further combined with extra (i.e., insulative) clothing during training to increase the stimulus. Immersion should be undertaken at water temperatures of around 40°C to induce adaptation while remaining tolerable (**Figure 2**). Although not as specific as exercise heat acclimatization *per se*, both passive and active methods of heat acclimation can be used to accommodate taper and travel requirements.

HYDRATION FOR PERFORMANCE AND RECOVERY

Although, heat dissipation relies on sweat evaporation, a caveat to this may be the progressive dehydration that ensues, if sweat losses are not adequately replaced by fluid consumption (Sawka et al., 2007; Maughan and Shirreffs, 2010). While dehydration exacerbates heat stress (Sawka et al., 2015), the magnitude may be lower during real-world competition than previously estimated in a laboratory study (Goulet, 2013). Nevertheless, hydration prior to, during and following exercise is important for athletes to perform well and ensure their safety in the heat; particularly during the heat acclimatization period due to the increase in sweat rate. It should however be acknowledged that

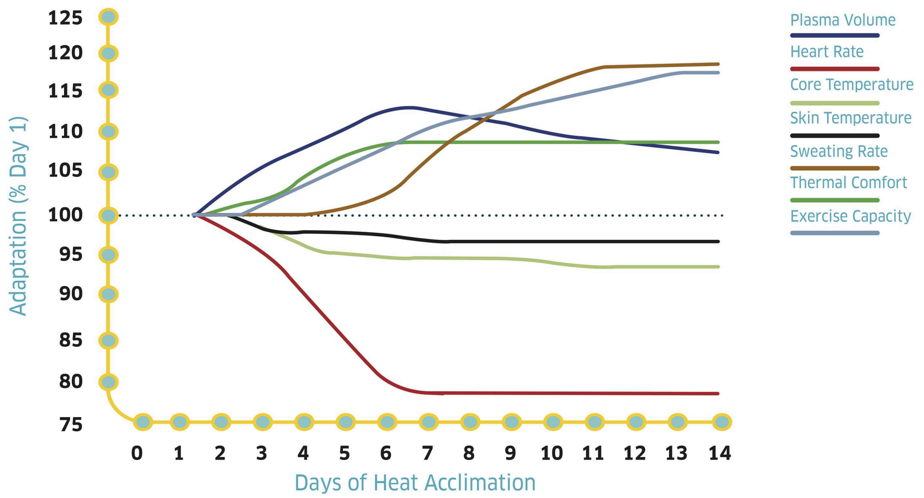

FIGURE 1 | Time course of heat acclimation adaptations with repeated training in the heat. Adapted with permission from Périard et al. (2015).

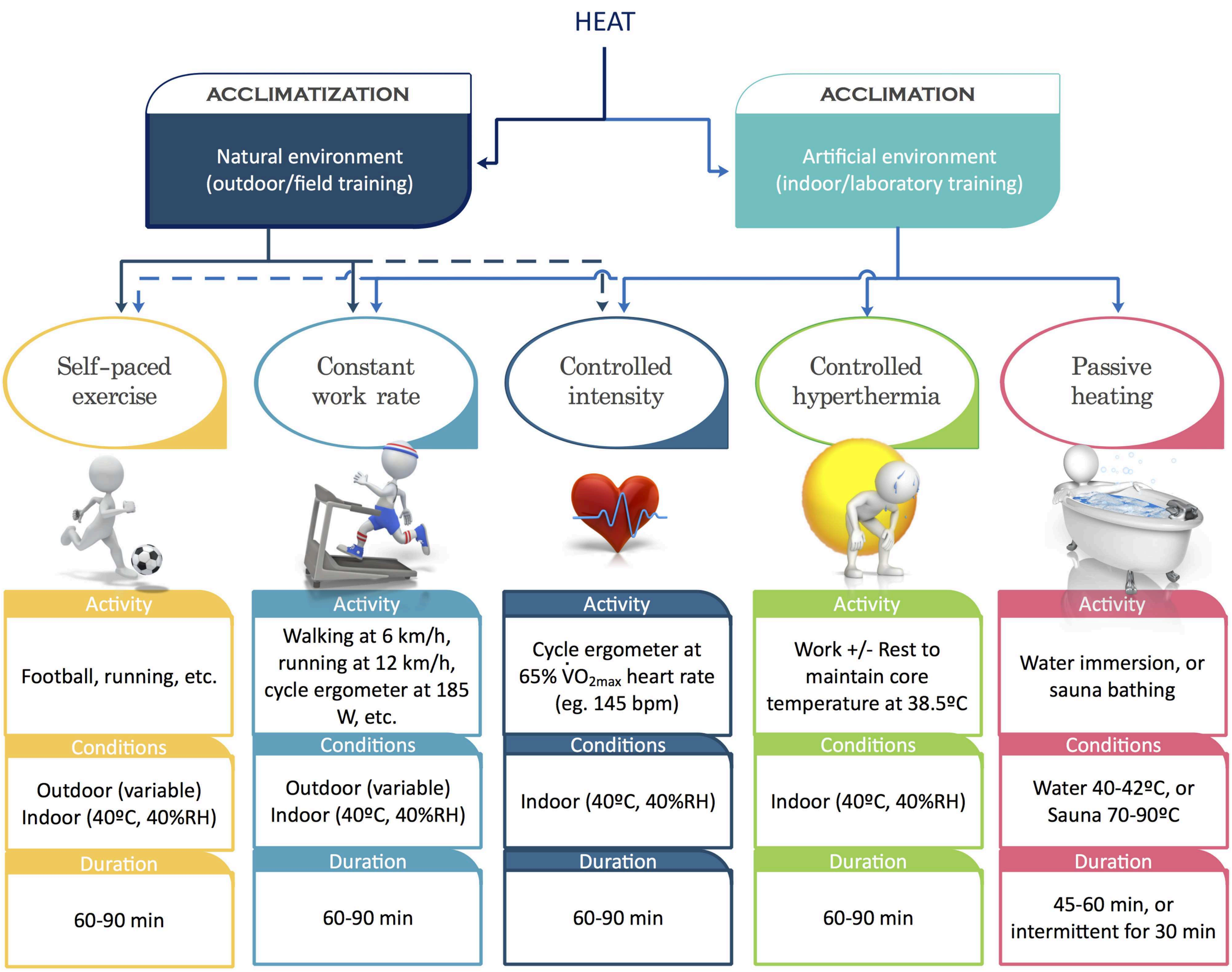

FIGURE 2 | Various methods for heat acclimatization/acclimation. Adapted with permission from www.ephysiol.com. RH, relative humidity; W, watt; bpm, beat per minutes.

an acute increase in fluid absorption will result in an increase in urine excretion, and that the body will need a few days to adapt (Racinais et al., 2015a). During the acclimatization period, recovery drinks should include sodium to compensate for the sweat losses, whilst maintaining the usual requirements in carbohydrates and protein to optimize recovery (Racinais et al., 2015a). In this context, milk is a suitable recovery drink covering both the exercise recovery and re-hydration needs (Maughan et al., 2016).

During exercise, and especially competition, drinking to thirst has been shown to be adequate for exercise lasting between 1 and 2 h in cool environments (Kenefick, 2018). However, during exercise in the heat, a planned drinking strategy may further optimize performance, especially during high-intensity activities lasting longer than 90 min (Kenefick, 2018), for which athletes may require carbohydrates. "Heavy and salty" sweaters (e.g., with a sweat-rate of 3 L/h and a sweat sodium concentration of 70 mmol/L) may also need sodium supplementation (Racinais et al., 2015a). Drinking plans should be targeted toward preventing body mass losses exceeding 2–3%, but never to the extent where it might increase body weight (Kenefick, 2018), as over-hydration can result in serious (potentially deadly) hyponatremia (an imbalance of the salts in the body; Hew-Butler et al., 2015). Athlete should therefore measure their change in body weight during training in the heat simulating the competition to estimate their fluid need several weeks before competing. Hydration in distance running is however limited by the absorption limits of the gut (~1.2 L/h) and by the possibility to drink while running. The priority should therefore be on limiting pre-event dehydration and optimizing recovery.

WARM-UP OR PRE-COOLING BEFORE COMPETITION?

Warming-up before an intense exercise or a competition has numerous physiological and psychological benefits improving performance (Racinais et al., 2017). However, warming-up in a hot environment would exaggerate the increase in core temperature and limit heat-storage capacity, thereby affecting prolonged exercise performance in the heat (Racinais et al., 2017). Consequently, in order to minimize unnecessary heat exposure and heat gain, the warm-up should be tailored to the environmental conditions (e.g., warm-up in the shade, modified exercise types and intensity, lower duration) and combined with cooling aids.

Many athletes commonly use pre-cooling techniques (**Figure 3**; Périard et al., 2017), a strategy that may seem counterproductive and potentially incompatible with warming-up. Pre-cooling refers to the lowering of pre-exercise body temperatures to lower thermal strain during the ensuing exercise task (Marino, 2002; Choo et al., 2018). A 0.5°C decrease in pre-exercise core temperature is often the desired goal of a pre-cooling strategy, whilst a 0.3°C decrease is generally considered the physiological minimum to confer a thermoregulatory advantage (Marino, 2002). Common pre-cooling modalities such as cold water immersion (CWI), ice slurry ingestion and the use of cooling vests have been shown to achieve such reductions in core temperature within 30–60 min (Marino, 2002; Ihsan et al., 2010; Ross et al., 2013; Zimmermann et al., 2018). Nevertheless, factors such as body mass and thermal responses (e.g., shivering) may influence the effectiveness of a particular pre-cooling strategy (Marino, 2002; Quod et al., 2006). It is therefore imperative that intended (race) pre-cooling strategies are incorporated and trialed during training, and selected based on athletes' comfort, effectiveness and available resources. The development of ingestible temperature monitoring capsules, as well as cooling aids (e.g., specialized slushy dispensers and bottles, portable water baths, lightweight ice vests) have by far eased the logistical constraints associated with on-field temperature monitoring and administration of pre-cooling strategies. As such, practitioners are encouraged to utilize such advances during training to formulate optimal pre-race cooling strategies. CWI is regarded as the most effective modality to reduce body temperatures (Ross et al., 2013; Choo et al., 2018). However, although advances in equipment/product design have improved the feasibility of this modality in the field, implementing it around competition venues will likely be cumbersome. Indeed, immersion temperatures need to be controlled between 20 and 25°C to minimize adverse thermal responses and discomfort (Marino, 2002; Quod et al., 2006), thus requiring manpower, as well as access to large volumes of water, ice, and/or electricity.

The use of cooling vests offers a more practical approach to undertake in the field. These garments are designed such that it covers the entire torso, and facilitates heat removal primarily through conduction. Albeit, the cooling capacity of such garments can be limited due to a contact interface of only 5–10% of the total body surface area (Luomala et al., 2012) failing to lower core temperatures when worn during normothermic rest (Duffield et al., 2003; Quod et al., 2008), they are still effective to limit excessive increases in core temperature during warm-up (Arngrïmsson et al., 2004; Hunter et al., 2006; Stannard et al., 2011; Katica et al., 2018). This is likely explained by the increase in circulation and heat production resulting from the warm-up, which may have better facilitated heat transfer to the vest. There may be some concerns though, regarding the potential increase in energy expenditure during warm-up, due to the added weight incurred by the vest. However, advances in technology and product design have resulted in vests weighing as little as 0.5 kg (Eijsvogels et al., 2014), with the commonly investigated vest by Artic Heat weighing 1.5 kg (Bogerd et al., 2010). Nevertheless, concerned athletes may opt to slightly reduce their warm-up running speed to compensate for the increased metabolic cost associated with utilizing the vest (Arngrïmsson et al., 2004), or combine with other practical strategies (described below), limiting the use of the vest during the more static components of the warm-up.

The ingestion of ice slurries or cold fluids is another practical modality which has gained considerable adherence amongst athletes (**Figure 3**; Périard et al., 2017). The underlying premise is that ingesting ice or cold fluids offer an additional avenue for heat transfer as the ingested bolus equilibrates with internal body temperature. The ingestion of an ice slurry over cold water has

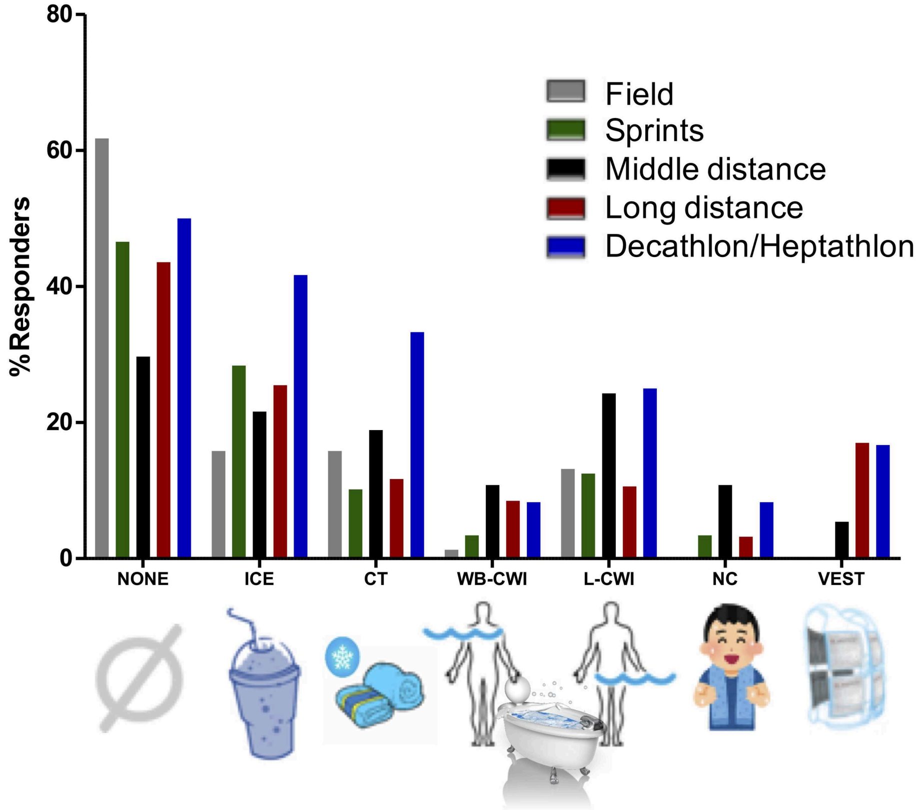

FIGURE 3 | Intended use of cooling strategies at the 2015 Beijing IAAF World Athletics Championships (Périard et al., 2017). ICE; ice ingestion; CT, cold towels; WB-CWI, whole body cold water immersion; L-CWI, lower limb cold water immersion; NC, neck collar; VEST, cooling vest.

been suggested to increase the potential for heat transfer, owing to the additional thermal energy required to convert ice to liquid (334 kJ/kg). Approximately 7 g/kg body mass of ice has been shown to typically induce a core temperature decrease of about 0.5°C (Ihsan et al., 2010; Siegel et al., 2010; Zimmermann et al., 2018). It is a mobile and flexible strategy which can be used prior to, and/or assimilated into the warm-up routine. However, ice or cold fluid ingestion has been shown to markedly reduce sweat rates through afferent feedback from thermoreceptors within the gut or stomach regions, potentially decreasing the evaporative potential for heat loss (Morris et al., 2014, 2016). Thus, caution is warranted when considering the use of ice or cold fluids in competition environments with high evaporative potential (e.g., dry and windy environments); whereas, when evaporative heat loss is minimal (e.g., humid environments), the decrease in sweat rate by ice ingestion may be beneficial in preserving blood volume, whilst facilitating internal cooling. Overall, ice and cold fluid ingestion are appropriate strategies to be implemented during warm-up.

Pre-cooling interventions can be mixed [e.g., cooling vests (torso) plus cold towels (neck and head regions), while drinking ice slurry] as benefits are proportionate to the body surface area cooled and the duration of cooling (Duffield et al., 2009; Minett et al., 2011, 2012; Soo et al., 2019).

MITIGATING THE HEAT STRESS DURING THE COMPETITION ITSELF

Cooling strategies may also be implemented during an event (i.e., mid-cooling) for immediate impact on performance (Stevens et al., 2017). While mid-cooling strategies may include the dousing of cold fluids on the head and facial regions, use of cooling garments or collar, as well as the ingestion of cold beverages or ice (Ansley et al., 2008; Minett et al., 2011; Stevens et al., 2013; Riera et al., 2014; Schulze et al., 2015; Sunderland et al., 2015; Périard et al., 2017); water dousing and ingestion are probably the only feasible strategies in athletics, and may be limited to endurance events on the road (i.e., marathon and race walks). Indeed, mid-cooling is not a relevant ergogenic aid for field, sprint and middle-distance events, and though may be relevant, not feasible in long distance track events. An exception might be the IAAF World Athletics Championships held in Beijing, where water stations were made available during the 5,000 m final. While the use of cold fluid ingestion and dousing can be seamlessly combined, the relative benefit of these strategies seem to be highly influenced by the environmental conditions. In humid environments, cold fluid ingestion, although reducing sweat response (Morris et al., 2014, 2016), may attenuate the increase in core temperature and minimize the decline in blood volume; whilst water dousing though offers a limited cooling effect (as evaporative potentials are highly diminished in humid environments) but may confer some perceptual benefits, although such advantages may be largely transient (Riera et al., 2014; Schulze et al., 2015; Tyler et al., 2015). Conversely, in dry and windy environments, water dousing increases the evaporative potential and hence body heat dissipation, whilst the ingestion of cold fluids has been shown to exaggerate the increase body temperatures by reducing sweat rates (Morris et al., 2014, 2016). Regardless, when deciding on ingestion and dousing strategies during race, it mainly depends on the immediate athlete needs: drink if thirsty, pour if hot (Morris and Jay, 2016).

Athletes should also protect their eyes by wearing UV ray blocking sun-glasses in a dark tint (i.e., grade 3) and their skin by using non-greasy sun-screen (water-based sun screen should be preferred to oil-based sun-screen that may affect sweating). Lightly colored clothing can also minimize the effect of the sun's radiation, but clothing should not impair sweat evaporation.

MANAGING EXERTIONAL HEAT ILLNESS

Exertional heat stroke (EHS) is the most severe form of heat illness, typically characterized by a neuropsychiatric impairment coupled with a high core body temperature (>40.5°C). Athletes will likely have no sequela if their internal body temperature is reduced <40°C within 30 min (Stearns et al., 2017), but may however suffer permanent disability beyond this point and even death if treatment is postponed by more than 1 h.

In order to minimize the number of minutes the EHS patient is hyperthermic, it is crucial that EHS is considered as one of the primary possible diagnosis when an athlete has collapsed or is struggling during intense exercise in the heat. The other potential medical issues need to be quickly considered and excluded, including cardiac conditions, asthma, exertional hyponatremia, head injury, exertional sickling, diabetes, and anaphylaxis; and core body temperature should be assessed immediately to quickly confirm or invalid the EHS diagnosis. When athletes have been exercising intensely in the heat, it is essential that rectal temperature is utilized to determine if the athlete is severely hyperthermic or not (Casa et al., 2015). Signs of central Nervous System (CNS) dysfunction (e.g., confusion, altered consciousness, coma, convulsions, agitation, combativeness, disorientation) coupled with a rectal temperature >40.5°C (>105°F) indicate an EHS episode that needs immediate attention.

As soon as diagnosed, EHS should be immediately treated by CWI. Research has verified that CWI has the fastest cooling rates, hence should be the cooling mode of choice (Casa et al., 2015; Demartini et al., 2015). In controlled athletic venues such as practices, endurance sports events, and competitions conducted in warm/hot environments, it would therefore be recommended to have CWI set-up at convenient locations at the venue or course. A few tips to assure a successful immersion procedure include: consistently stir the water during cooling, cover as much skin surface area as possible, drape sheet under armpits to stabilize patient in tub, use rectal thermistor so that core temp can be monitored during cooling, and utilize water temperatures around 10–15°C (although a wide range of water temperatures will provide effective cooling rates). Remove from the CWI when the EHS patient reaches about 39°C. To minimize the duration at which an athlete remain >40.5°C, it is mandatory to cool-first/transport second (Belval et al., 2018). For instance, if an EHS patient needed to wait for the ambulance to be called/arrive/on-scene/transport/enter hospital/establish cooling at hospital; well over the established 30 min will be lost before even before aggressive cooling would begin. To increase the likelihood of a successful treatment outcome of EHS cases, it is essential to work with local ambulance/hospital services so that the concept of cool-first/transport second is firmly established as part of the medical policy prior to a time of crises.

CONCLUSION

In summary, hot and humid ambient condition may play a major role in numerous athletic events. Fortunately, athletes have a toolbox of countermeasures with various efficacy and feasibility. The most important is to plan ahead by training in the heat for 2 weeks. Hydration should also be considered during the preparation and recovery phases as it is not always feasible to drink during the event. Depending on thirst and perception, the water available during competition may be ingested or doused around the head. Another important consideration is to limit unnecessary increases in core temperature by adapting the warm-up with some cooling strategies such as ice-vest or cold/iced drinks, and avoiding clothing or accessories limiting sweat evaporation. Medical response should focus on rapid cooling by having CWI tubs already set-up to cool first / transport second.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The Use of Technology to Protect the Health of Athletes During Sporting Competitions in the Heat

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During the 2019 IAAF World Championships in Athletics in Doha and the 2020 Olympic Games in Tokyo, minimum daily temperatures are expected to be in excess of 30°C. Due to the metabolic demands of the sporting events and the high environmental temperatures, the risk of exertional heat stroke (EHS) is high. Careful planning by event organizers are needed to ensure that athletes are protected from irreversible long-term health damage, or even death during sporting competitions in the heat. Efforts typically have included standard medical plans, equipment, protocols, and expert medical teams. In addition, the importance of responding quickly to a hyperthermic athlete cannot be understated, as minimizing treatment time will greatly improve the chances of full recovery. Treatment time can be minimized by notifying medical personnel about the health status of the athlete and the extent of any pre-competition heat acclimatization. Technology that allows the live transmission of physiological, biomechanical, and performance data to alert medical personnel of potential indicators of EHS should be considered. Real time monitoring ecosystems need to be developed that integrate information from numerous sensors such as core temperature-monitoring "pills" to relay information on how an athlete is coping with competing in intense heat. Medical/support staff would be alerted if an athlete's responses were indicating signs of heat stress or EHS signs and the athlete could be withdrawn under exceptional circumstances. This technology can also help provide more rapid, accurate and dignified temperature assessment at the road/track side in medical emergencies.

Keywords: hot environment, heat stroke, exertional heat illness, olympics, world championships, health, athlete protection

INTRODUCTION

The 17th IAAF Track and Field World Championships will be held in Doha (Qatar) from 27th September to 6th October, 2019. This will be one of the most anticipated sporting events of the 2019 calendar, with an estimated 3,500 athletes, 40,000 international guests, and more than 2,000 media personnel. In addition to being one of the most hotly anticipated events of the year, daily and peak temperatures are expected to be ∼32 and 40°C, respectively, with a relative humidity of ∼60% (Time and Date, 2018).

While the relevant governing bodies and authorities are expected to take all essential measures to avoid athletes competing in extreme heat (e.g., midnight marathon and the removal of all morning sessions), the reality remains that the minimum daily temperature during events such as the marathon is likely to be ∼30°C [as it was in 2018 during the same day (Time and Date, 2018)]. The impact of exercising under such extreme environmental conditions will increase the likelihood of developing exertional heat illness (EHI), which is associated with a core body temperature above 40°C (Knochel, 1974). The symptoms of EHI include coordination difficulties (Hubbard and Armstrong, 1988), reduced cognitive function (Lieberman et al., 2005), impairment in endurance performance (Galloway and Maughan, 1997; Nybo et al., 2014), and eventually exertional heat stroke (EHS) followed by collapse (Kenefick and Sawka, 2007). There are cases of fatal EHS in environmental conditions similar to those which will be experienced in Doha and Tokyo. For example, several cases of fatal EHS have been reported in novice runners performing long-distance road races (>10 km) at 24–26°C and a relative humidity ranging from 60 to 66% (Hanson and Zimmerman, 1979), and also in a runner performing sprint sets at 29°C (relative humidity not reported) (Graber et al., 1971). There are indications that the greatest risk for EHS occurs when the wet bulb globe temperature (WBGT) surpasses 28°C during high-intensity exercise and/or strenuous exercise that lasts more than an hour (Armstrong et al., 2007). The WBGT is a climatic index used worldwide by event organizers, and it is calculated from the air temperature, humidity, mean radiant temperature, and wind speed (Casa, 2018). This index applies a weighted average between the natural wet-bulb temperature (which indicates the true capacity of the air to evaporate water according to its relative humidity and velocity), the dry bulb temperature, and the solar radiation (globe temperature; Casa, 2018). As an environmental indicator, this index does not account for metabolic heat production or clothing, and therefore cannot predict heat dissipation (Sawka et al., 2011). Therefore, EHS can occur even during apparently normal environmental conditions, following WBGT indications (Casa et al., 2015), which questions the suitability of using an environmental index only in sporting events. Hosokawa et al. (2018) have recently developed 36-year (1980–2016) modeled climatologic datasets for the Japanese and Qatar venues for the upcoming events, showing the hourly WBGT.

Time is also critical in EHS management as an athlete is more likely to suffer long-term disability if treatment does not commence within 30 min and the risk of death increases if treatment is delayed by more than 60 min (Adams et al., 2015). A recent case that highlights the importance of a rapid intervention during EHS is the collapse of the Scottish marathoner Callum Hawkins during the 2018 Commonwealth Games in Queensland (Australia) in an environmental temperature of 30°C. Callum was leading the race and was 2 km from the finish line when he first collapsed. Although medical assistance arrived several minutes after his collapse, the event organizers were heavily criticized for insufficient medical care (The Guardian, 2018). This unfortunate event warrants the introduction of additional measures to those normally in place in competitions in warm-hot weather conditions, especially considering EHS is the second largest cause of death in sport, after cardiovascular events (Casa and Stearns, 2016). Demartini et al. (2015) examined 274 cases of EHS with body temperatures above 40°C and showed that immediate temperature evaluation and CWI treatment resulted in 100% survival. This illustrates the importance of a prompt recognition and immediate treatment during EHS. Moreover, two major international events are planned within the next year (i.e., the 2019 IAAF World Championships in Doha and the 2020 Olympic Games in Tokyo) which highlights the need to characterize the thermoregulatory responses of athletes competing in high-risk sports (e.g., race walking, triathlon, marathon running) to effectively protect the health of athletes and adapt current policies. A recent report documented 57 deaths and more than 18,000 people taken to hospitals due to heat-related medical issues over the week starting the 29th July, 2019 in Japan; the exact date of the Tokyo Olympics next year (The Japan Times, 2019). This is a timely reminder of the magnitude of the potential risks if organizers, athletes, spectators and the general population are not fully informed of the importance of taking appropriate preventive measures. Additionally, many of the athletes competing in Doha 2019 will attend the 2020 Olympic Games in Tokyo next summer. These athletes should also be aware that an EHS event requires full recovery prior to returning to training. Concerted efforts to enhance medical provision will also provide an essential legacy for future top-level competitions such as the Olympic Games planned in hot and humid climes of Paris (2024) and Los Angeles (2028).

Although the safest "return to play" strategy after an EHS event remains to be determined, previous research suggests resting up to 21 days before returning to exercise (Casa et al., 2015). However, there are reports stating that up to 60 days of rest may be necessary (Lopez et al., 2018). In the case of incomplete recovery from EHS, the athlete may become heat intolerant, exhibiting an abnormally high physiological response to exercise in the heat (Casa, 2018). Potential residual effects of EHS occurring in Doha, will likely compromise the athlete's preparation and performance in the 2020 Tokyo Olympics. The long-term adverse effects in individuals who have suffered from EHS depend directly upon the duration of hyperthermia, the intensity of shock, the rate of cooling, and the prompt recognition and treatment of associated severe complications (Shapiro and Seidman, 1990). It is worth noting that body temperature at collapse is usually between 41.1 and 43.3°C, and athletes are likely to have been exercising above critical body temperature without apparent signs of EHI for an unknown amount of time when loss of consciousness is observed (Adams et al., 2015). Those patients who survive severe EHS often show cerebellar damage and cerebellar ataxia with marked dysarthria and dysmetria (Yaqub, 1987; Royburt et al., 1993). In fact, residual neurological damage has been observed in up to 20% of EHS survivors (Bouchama and Knochel, 2002). Accordingly, previous research presented persistent neurological deficits and personality changes 3 years (Lin et al., 1991) and 11 years (Mehta and Baker, 1970) after EHS.

The Summer Olympics over the past three decades have been held in July or August, recognized as an ideal time for television networks to cover the event, but highly problematic for organizers who must protect athletes from the hot weather in several of the host cities such as Los Angeles (1984), Athens (2004), Beijing (2008), and Rio de Janeiro (2016). The hot and humid conditions can negatively impact sporting performance, and this effect is most pronounced during endurance events as can be illustrated by comparing the fastest men's marathon times during an Olympic year with the winning time at the Olympic marathon (**Figure 1**). While there are other contributing factors to the slower Olympic marathon times (e.g., slower courses, tactical races, absence of pace makers, medals on offer rather than prize money), the hot and humid conditions clearly play a major role.

There are numerous strategies that can be adopted by the athlete prior to and during competition to attenuate the rise in core temperature, although heat acclimation/acclimatization appears to be the most beneficial. Acclimatization differs from acclimation in that the adaptive characteristics are augmented in a natural climate or environment, whereas the stimuli for acclimation is artificially induced, typically through an environmental chamber where ambient conditions are altered (Racinais et al., 2015). The primary adaptations following heat acclimatization include a decrease in core temperature (Périard et al., 2015), increased control of cardiovascular function (Armstrong and Maresh, 1991), and increased sweat rate with earlier onset and more dilute sweat (Mack and Nadel, 1996), all of which facilitate an improvement in performance in both hot and temperate environments (Lorenzo et al., 2010). There are multiple factors to consider in order to optimize heat acclimatization (Armstrong and Maresh, 1991), and protocols range from short (e.g., $<$7 daily exposures) to long (e.g., $>$15 daily exposures) durations. However, the maximal adaptation to a specific environment will result from simulating the environmental and work characteristics of the real environment one wishes to perform (Périard et al., 2015). Therefore, it is advisable that all athletes competing in endurance events (especially in events longer than 1,500 m) in extremely hot conditions such as those expected during Doha 2019 and Tokyo 2020, should undertake a long-term ($>$15 daily exposures) heat acclimatization, while exercising at intensities similar to that expected during the competition (Périard et al., 2015). Casa et al. (2009) highlighted the need for exercise duration and intensity to be gradually increased to avoid potential EHI during heat acclimatization. For optimal heat acclimatization to occur, a core temperature above 38.5°C is necessary (Patterson et al., 2004; Garrett et al., 2009). However, until now, such controlled hyperthermia during exercise required a laboratory setting to monitor core temperature in real time, albeit acclimatization is possible by prescribing the training intensity in hot ambient conditions using heart rate (Périard et al., 2015). In addition to heat acclimatization, there exists other, acute methods of attenuating rises in core temperature, known as "cooling strategies" before or during the sporting event (Ross et al., 2013). However, athletes taking these measures are still at risk of suffering from EHS, especially considering the difficulty of identifying signs of EHS.

Given the dangers associated with competing in extreme hot conditions and the likelihood that this occurrence will become more common, there is an urgent need to develop and implement the latest technologies to further our understanding of the thermoregulatory and physiological responses of elite athletes competing in extreme environmental conditions. The focus of this perspective is to examine potentially useful future innovations to prevent EHS. One such technological development allows the live transmission of physiological, biomechanical, and performance data that is able to alert medical personnel to abnormal perturbations of athletes and officials and save precious minutes in a medical emergency. Therefore, the aim of this perspective in conjunction with other related papers in this edition, is to raise awareness within the current policies to safeguard the health of athletes through innovative technologies.

TECHNOLOGICAL AND PRACTICAL APPROACHES

The application of wearable technology in recreational and elite sport is replacing traditional laboratory testing since wearables allows the assessment of numerous physiological and biomechanical responses and performance in real-life situations. However, a recent review highlighted the lack of quality assessment procedures (i.e., rigorous validity and reliability tests) that demonstrate the efficacy of an ever-increasing number of wearables (Peake et al., 2018). This review highlighted that only 5% of the commercially available wearables have been suitably validated, which make it difficult for athlete, technical or medical staff to identify high-quality and useful wearables (Peake et al., 2018). Notably, the most severe form of EHI (i.e., EHS) cannot be studied in the laboratory due to the risk of permanent damage to participants. As a consequence, the use of wearable sensors to measure body temperature has increased to enable data collection from individuals competing in hot ambient conditions. Monitoring of skin temperature has been divided into two subcategories (Tamura et al., 2018): the tach-type thermometers which are sensitive non-disposable wearable prototype devices that are applied directly to the human body using a variety of materials such as Tempdrop (Tempdrop, 2019), Ran's night (Ran's Night, 2019), and iFiever (Vipose Smart Thermometer, 2019). The second category is the patch-type wearables, which are wireless and electronic miniaturized disposable sensors that are attached to the skin surface by the application of an adhesive patch to any part of the body such as VitalConnect (VitalConnect, 2019), FeverFrida (FeverFrida the iThermonitor, 2019), STEMP (Smart Temperature Patch, 2019), TempTraq^{TM} (TempTraq Landing, 2019), Fever Scout (Fever Scout, 2019), and Fever Smart (Feversmart). These allow the continuous monitoring of skin temperature, human skin hydration through the assessment of thermal conductivity, as well as blood variables (Tamura et al., 2018). These sensors are usually made from plastic materials or a small amount of silicon, which is used as a membrane around the core of the sensors. All

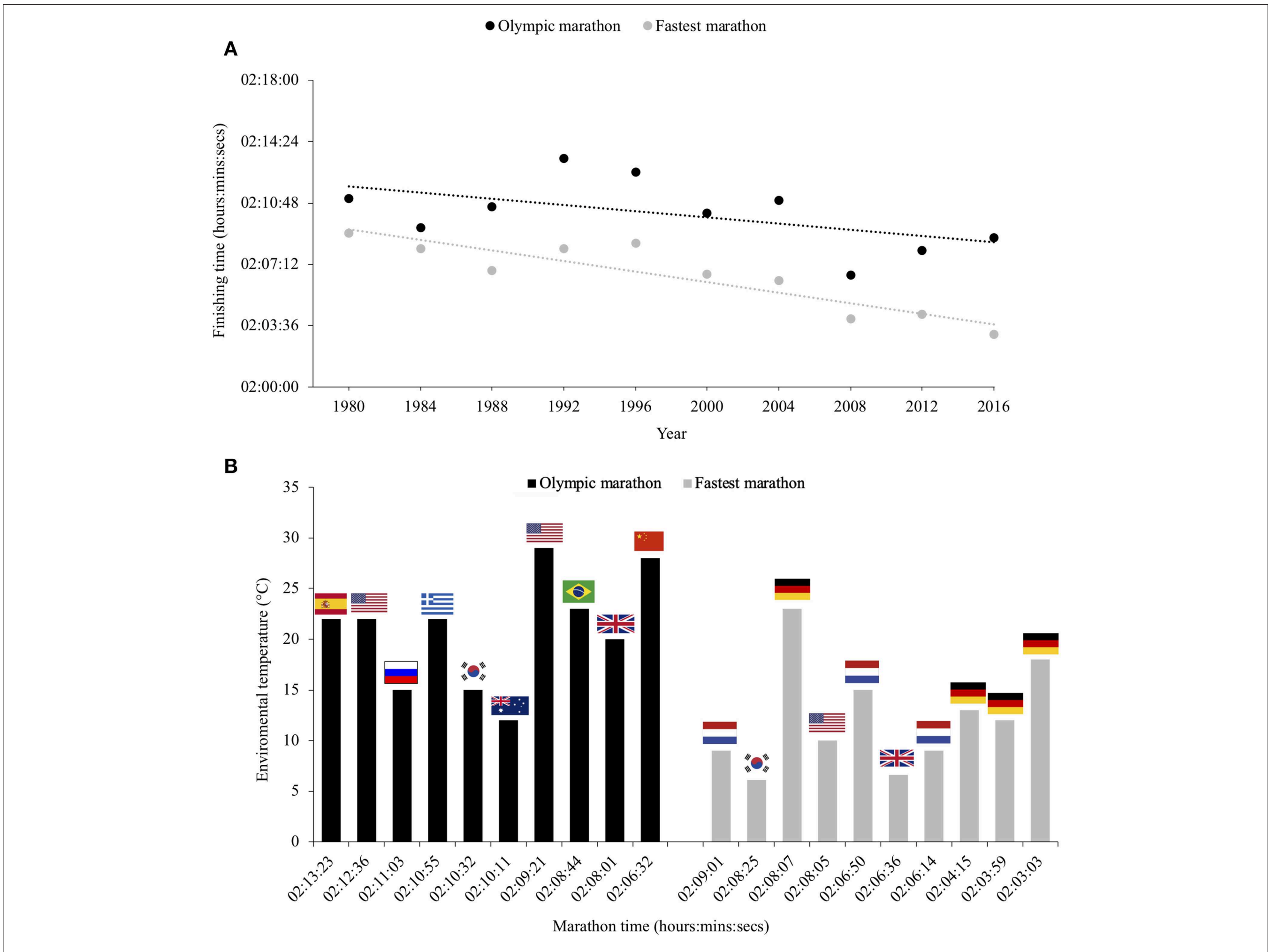

FIGURE 1 | Comparison of the fastest men's marathon times during Olympic year with the winning times at the Olympic marathons over the past four decades **(A)** and the temperature disparity between these marathons **(B)**.

these sensors are designed to measure skin temperature (Tamura et al., 2018), but none adequately reflect core temperature. There is also an important gap in the scientific literature examining the validity and reliability of such devices, which also questions their use (Casa, 2018). It is essential, therefore, that independent research institutions are set up to regulate the quality standards of wearable technologies to support entry into the market when sufficient validity and reliability has been demonstrated (Düking et al., 2018). Given these and other limitations, but also the need to accurately measure core temperature *in situ* in the competing athlete, a number of technological developments are needed. One such direct method to continuously monitor core temperature is the use of an ingestible thermometer pill. This method is gaining popularity in sport and is already extensively used in numerous ambulatory settings (Casa, 2018). There are at least three different ingestible pills systems in production and development: HQInc, Philips/Respironics, and BodyCap (Casa, 2018). Of these, the ingestible pill manufactured by BodyCap is the most miniaturized core temperature-monitoring sensor (1.7 g), which facilitates its tolerability and use. The pill is wirelessly connected to an external monitor device, although the main limitation of this technology is that the pill needs to be in close proximity to the monitor to enable live feedback and transmission. To date, none of these commercially available pill systems can provide the desired real time *in situ* assessment.

Given the need to better protect the athlete exercising in extreme conditions (or other personnel such as military and members of the emergency services), we are attempting to develop live-transmitting technology that allows the tracking of multidisciplinary data within a single application. This innovation is a system that provides live feedback of land and air temperature, heart rate, and a range of physiological and biomechanical parameters facilitated through a Cloud-based portal allowing the athlete support/medical team to view the data on a desktop, tablet, or a smartphone in real time anywhere with internet access or mobile access (Düking et al., 2018; Muniz-Pardos et al., 2018; **Figure 2**). An early prototype version of this application was recently trialed in elite marathoners training at

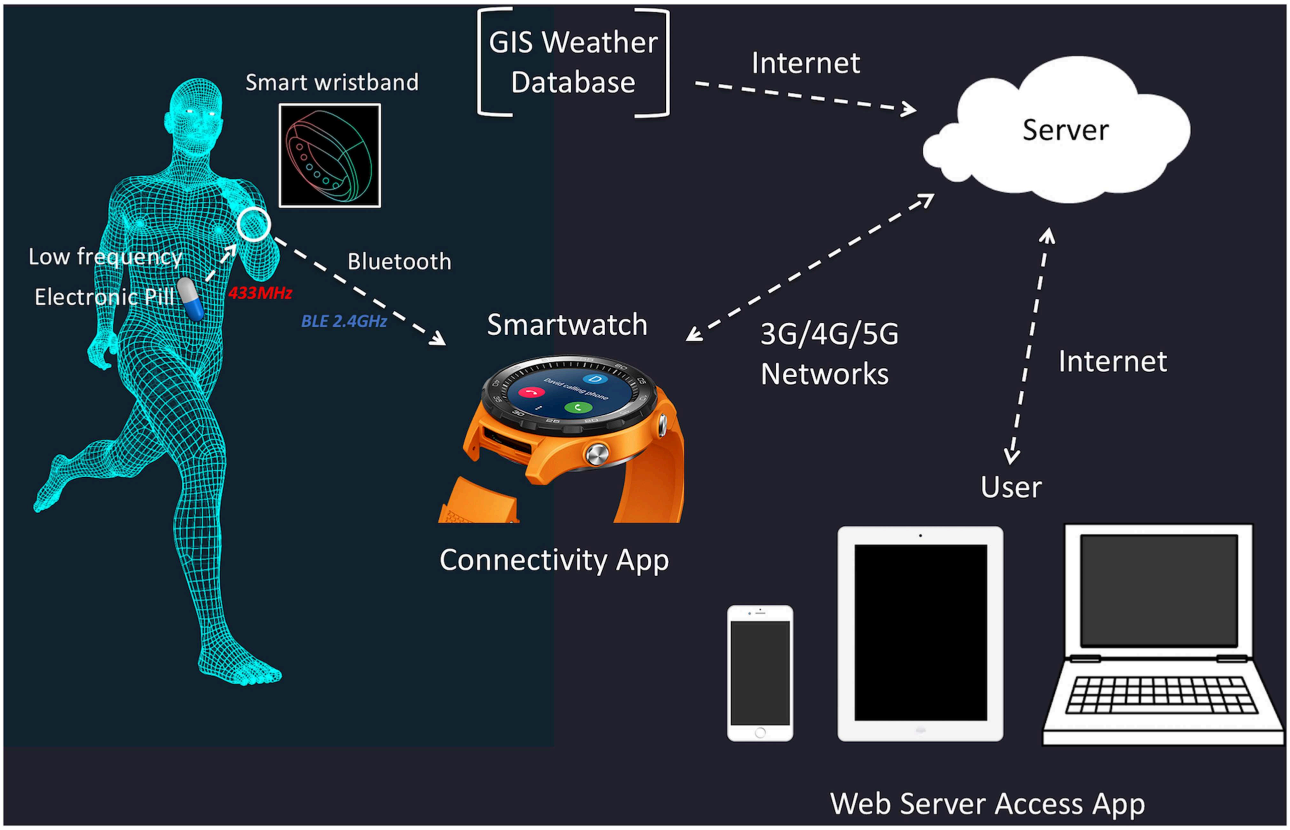

FIGURE 2 | Smart activity and temperature monitor to enhance safety during sporting events with particular reference to athletes, officials, and workforce at increased risk. Adapted from Düking et al. (2018) with permissions from Wolters Kluwer Health, Inc.; License number: 4654951032268.

altitude in Iten (Kenya) with the addition of sensors that also identified foot strike patterns (e.g., pitch angles, strike angles, contact times), transmitted second by second to a portal database (Muniz-Pardos et al., 2018). This feasibility study illustrated the capacity of wearable technology to monitor fatigue, injury or even EHS signs through biomechanical assessment. Given the threat of the internet, WIFI, and other traditional networks being compromised or hacked during high profile sporting events such as the Olympics, alternative approaches to transmit data and communicate are needed. Notably, Firechat and Bluetooth Bridgefy Apps have recently been used with much success by protesters to avoid being traced by authorities (BBC News, 2019). The mobile network, especially as 5G becomes more widely available, represents, for now at least, the preferred option to transmit data and communicate effectively.

The development of an ecosystem that allows the real time assessment of body temperature but also other physiological (e.g., cardiorespiratory responses) and biomechanical responses (e.g., imbalances and irregular strides of the lower limbs) of an athlete, could undoubtedly help protect athletes from EHS by helping alert medical staff of impending conditions such hyperthermia. For example, wireless foot-worn inertial sensors (FWIS) with a wireless foot insole pressure system (FIPS) and dedicated signal processing algorithms have recently been developed that can detect spatiotemporal variables (e.g., contact time, stride frequencies, ground reaction forces, and strike angles) of the foot and running mechanics (Mariani et al., 2013; Falbriard et al., 2018; Muniz-Pardos et al., 2018; Peake et al., 2018). This quantification of the kinetic and kinematic modulation of the lower limbs (i.e., loading rates, impact forces) is able to provide unique insights into the foot biomechanical characteristics and therefore running mechanics of athletes across different running and environmental conditions. It is known that alterations in running technique can substantially influence the neuromuscular and kinematic characteristics of running (Lieberman et al., 2010; Udofa et al., 2019). There is also some evidence that foot biomechanical characteristics such as contact and swing time can be modulated during strenuous exercise in response to heat stress (Girard et al., 2016). These technological advances will undoubtedly aid scientists, physicians, and athletes to make more informed decisions about the effectiveness of therapeutic methods, preventive interventions, and other medical approaches.

Another convenient wearable recently launched is the utilization of smart bottles linked to a smart device to track fluid intake. The smart drinking device launched by a major drinks company, incorporates an auto spout, auto seal, and achieves a high flow rate and is able to communicate digitally with a "band aid-like" sweat patch claimed to track the hydration status of the athlete (Burke, 2019). The utilization of such technology along with other wearable technology transmitting numerous types of data in real time, will inevitably become the norm at major sporting events as international sporting federations seek to make their sport more interesting and accessible to their audiences. These technological developments can also be harnessed to help protect the health of athletes (and officials) from numerous conditions not confined only to EHS but can include many other health-related conditions such as concussion and cardiac sudden death and help make more objective and informed decisions about leaving and/or returning to the field of play. The implementation of real time technology would potentially permit the earlier identification and more effective treatment management of athletes by medical personnel during a medical emergency.

It is unquestionable that within a decade or even less, wearables will be worn at all times and data collected will be fed into machine-learning algorithms to monitor vital signs, identify abnormalities and track treatments, so that medical problems can be detected earlier (Xu et al., 2019). An example of this technology is the novel self-applied wearable electrocardiogramme patch, which can monitor heart dynamics for 14 days. Despite only limited data, there are some encouraging results that show this wearable to be more effective in detecting signs of atrial fibrillation than occasional medical monitoring (Steinhubl et al., 2018). Tandon and de Ferranti (2019) have recently described the capacity of wearable sensors to alert the medical team of cardiovascular disease from real time continuous physiological data monitoring in an infant population. Such technological developments will transform the health-care system from hospital-based interactions to more continuous home-based care (Tandon and de Ferranti, 2019). Wearable chemical sensors to monitor body fluids are increasingly being described (Matzeu et al., 2015; Ray et al., 2019). In particular, blood monitoring has been extensively used in the medical field for the last few years to measure a number of parameters, although recent research recommend the use of non-invasive chemical analysis of biofluids such as sweat, tears, saliva, or interstitial fluids, providing minimal risk of harm or infection and are generally more user friendly (Kim et al., 2019). Of these easily accessible body fluids, sweat has been particularly amenable to the detection of sodium (Bandodkar et al., 2014), glucose (Lee et al., 2017), and lactate levels (Anastasova et al., 2017). All these parameters are potentially interesting to the sports physician/exercise scientist as markers of electrolyte balance and energy homeostasis. These necessary advances are encouraging leading many experts in the field to contend that we are facing the first generation of "biointegrated sensors," which will require close collaborations between materials and device engineers, scientists, and medical professionals to optimize the utility of this technology (Ray et al., 2019; Xu et al., 2019). The power of this technology can also be integrated into the fight against doping by the introduction of remote monitoring of molecules in sweat or blood. Such advances would also generate exciting new possibilities for checking an athlete's metabolism and aid the policing of doping in sport (The Guardian, 2016).

CONCLUDING REMARKS

Given the two upcoming high-profile sporting events conducted in extremely hot ambient conditions (Doha 2019 and Tokyo 2020), it is essential that event organizers and those responsible for the health of athletes, officials, work staff, and other populations at risk of EHS, are well-informed and prepared. Due to the extreme environmental conditions, it is critical for medical staff to recognize early the symptoms of EHS and to quickly and effectively intervene. The monitoring of an athlete's physiological responses such as core temperature, hydration status, and relevant biomechanical parameters and its transmission in real time to support/medical personnel will accelerate the recognition and treatment of any athlete suffering from EHS. The medical teams would be better equipped to recognize earlier EHS if they could be informed of the acclimatization strategies, history of EHI, current viral illnesses, and sleep diaries of athletes. These measures and technological approaches seem necessary to protect athletes and other populations at risk to perform at their best while minimizing the risk of serious illness or even death at these and future sporting events conducted in extreme environmental conditions.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the manuscript.

AUTHOR CONTRIBUTIONS

All authors contributed significantly to this manuscript.

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Influence of Race Performance and Environmental Conditions on Exertional Heat Stroke Prevalence Among Runners Participating in a Warm Weather Road Race

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The New Balance Falmouth Road Race held in Falmouth, Massachusetts, U.S. is a short distance race (11.26 km) that is well-known for high rates of exertional heat stroke (EHS). Previous research has documented the increased EHS rates with hotter and more humid weather conditions, yet did not explore the influence of race pacing on EHS risk. In this study, we leverage 15 years of data to investigate if runners who experienced an EHS moderate their average paces based on weather conditions and if there is a difference in average race pace between participants who experienced an EHS and other runners. Results indicate that runners who experience an EHS do not appear to reduce their average pace with increasing WBGT warning flag categories. In addition, runners who suffer an EHS run at a faster average pace than others, even when controlling for age, gender, race performance, and starting time WBGT. This suggests the important role of metabolic heat production as a risk factor of EHS. Since race pacing is a modifiable risk factor, our findings support the need for race organizers to actively encourage runners to adjust race pacing based on weather conditions.

Keywords: road race, exertional heat stroke, wet bulb globe temperature, race medicine, pacing

INTRODUCTION

Exertional heat stroke (EHS) becomes a major concern for race day medical service, especially in warm and hot weather races, where a rapid increase in number of medical tent visits is observed (DeMartini et al., 2014; Hosokawa et al., 2018). EHS occurs when one's thermoregulatory capacity is overwhelmed due to imbalances between metabolic heat production and heat dissipation by means of evaporation, radiation, convection, or conduction (Armstrong et al., 2007; Grundstein et al., 2017). In the context of outdoor exercise in the heat, the rate of rise in internal body temperature is directly influenced by the absolute evaporative requirement needed to maintain heat balance, which is increased as the air temperature, and work output increases (Cramer and Jay, 2016). When the maximum possible evaporative heat loss exceeds the rate of evaporative heat loss required, a state of uncompensable heat stress ensues (Cramer and Jay, 2016). During uncompensable heat stress, the sustained rise in body temperature could lead to cell anoxia, gastrointestinal permeability, cardiovascular collapse, and inflammatory reactions (Epstein and Yanovich, 2019). If the state is not corrected by adjustment (i.e., reduction) in metabolic heat production, the relative risk of exertional heat illness is high since the metabolic rate is the primary driver for heat storage (Santee and Gonzalez, 1998). Notwithstanding, exercise in hot environment (≈34°C) has shown to induce an anticipatory reduction in work output without an evidence of neuromuscular fatigue or influence from the rate of heat body heat storage, suggesting that sensory input from warm environment itself may also have influence on exercise pacing (Ravanelli et al., 2014). From these laboratory findings, the difference between runners who experienced EHS and those who did not may be reflected in their pacing strategy. EHS runners may have sustained faster pace exposing themselves to longer uncompensable heat stress while those who did not had attenuated their pace as the environmental temperature increased. Therefore, we aimed to retrospectively examine the influence of pacing on the likelihood of a runner experiencing EHS. We hypothesized that the pace of runners who experience an EHS would differ from non-EHS finishers.

MATERIALS AND METHODS

Study Design

We studied the interrelationship between meteorological conditions, race pacing, and cases of EHS at the New Balance Falmouth Road Race. The race is 11.26 km in length and is held annually in August in Falmouth, Massachusetts, USA (41.52°N, 70.67°W). Each year, ∼10,000 runners, ranging in status from novice to elite, participate in the race.

Race-Participant Data

Data on EHS cases were obtained from medical tent records for 15 years between 2003 and 2018 (no finish times were recorded in 2006). EHS was clinically determined based on a rectal temperature ≥40°C and associated signs of central nervous system dysfunction (e.g., delirium, altered mental status, aggression, hysteria). Only EHS cases where the participant finished the race were included in this analysis. The finish time was obtained for each of these individuals and average pacing was calculated by dividing finish time by race distance (11.26 km). In addition, information on the age, gender, and race status as elite or non-elite were available for both EHS and non-EHS finishers for the years 2014–2018 (New Balance Falmouth Road Race, 2019). In these 5 years, we used the race bib numbers to explicitly identify elite (bib numbers 1–100 for men and 101–200 for women) and non-elite (bib numbers >201) runners. We did not have these data for the years 2003–2013 and instead divided runners as "faster" or "slower" based on available finish times for 2014–2018. "Faster" runners were defined those with finish times ≤2 standard deviations from the mean and would have finish times consistent with those of elite runners but also some exceptional non-elite runners. This value ranged from ∼42–44 min between years, with an average of 43:33 min. Racers with times greater than the 43:33 min threshold were considered "slower" runners. Our sample of faster EHS runners was insensitive to the particular threshold used (42–44 min).

Lastly, incidence rates were computed as number of EHS finishers per 1000 finishers for the years 2003–2018, with the exception of 2012 and 2013 when the number of finishers were not available. The number of finishers for 2003–2011 were obtained from published results in DeMartini et al. (2014) and for 2014–2018 from the New Balance Falmouth Road Race website (New Balance Falmouth Road Race, 2019).

Meteorological Data

Meteorological data (e.g., dry bulb temperature, dewpoint temperature, and cloud cover) were collected from the nearest available weather observing station located at Otis Air National Guard Base (41.65°N, −70.52°W), which is ∼18.8 km from the race start and operated in joint effort between the National Weather Service, the Federal Aviation Administration, and the Department of Defense. Wet bulb globe temperatures (WBGT) were not routinely recorded during race events and were therefore computed from meteorological data using the Heat Stress Adviser (version 2005; Zunis Foundation, Tulsa, OK) software package (Coyle, 2000). Input data into this model includes air temperature, dewpoint temperature, cloud cover, and time of day. The model was developed for warm season conditions (May—September) and was tested in a variety of geographic regions in the U.S., including Oklahoma, Texas, Minnesota, and New York. WBGT estimates are accurate to ±1.1°C (Coyle, 2000; Zunis Foundation, 2005).

The WBGT was classified using the International Institute for Race Medicine (IIRM) heat stress flag color warnings for runners as low (green, <18°C), moderate (yellow, <18–23°C), high (red, 23–28°C), and extremely high (black, >28°C) risk for hyperthermia (Mears and Watson, 2015). The WBGT was determined at the start of the race (either 9 or 10 a.m. Eastern Daylight Time, depending on the year) and also computed as an average based on the race finish time for each runner suffering an EHS.

Statistical Analysis

All statistical analyses were performed using SPSS (Version 26; IBM Corporation, Aramonk, NY). The relationship between EHS incidence rates and starting time WBGT was assessed both graphically and using regression analysis. R^2 was used to identify the explained variance of the regression model.

Descriptive statistics (e.g., mean, standard deviation) were used to characterize average race pacing for EHS cases under different flag color warnings. Group differences in race pacing among flag warning categories for faster and slower EHS finishers were determined using one-way ANOVA. Statistical significance was set a priori at an alpha level of $\rho < 0.05$. The Shapiro-Wilk test of normality and Levene's test for equality of variances were used to ensure that conditions of the statistical test were met. For slow EHS finishers, four participants with race finish times over 1:50 were excluded from analysis as these outliers had average paces consistent with walking rather than running.

Finally, a one-way ANCOVA was conducted to compare any difference in average pacing between EHS and non-EHS finishers for the years 2014–2018 while controlling for age, gender, status as elite or non-elite and starting time WBGT. Statistical significance was set a priori at an alpha level of $\rho <$

0.05. Levene's test for equality of variances and normality checks were used to ensure that conditions of the statistical test were met.

RESULTS

Incidence

A total of 247 participants finished the race and experienced an EHS (243 when the four walkers were excluded) over the 2003–2018 period (**Table 1**). We identified 36 faster and 207 slower EHS finishers using race finish time to stratify the groups. The number of total cases ranged from a low of 5 in 2004 to a high of 38 in 2015, with an average number of 16.5 ± 9.7 per year. EHS incidence rates averaged 1.8 ± 1.16 per 1000 runners and ranged from a low of 0.90 in 2018 up to 4.59 in 2003.

Wet Bulb Globe Temperature

WBGTs were computed at the start of the race (**Figure 1**) and as an average exposure WBGT for each of the 243 runners experiencing an EHS over the length of their race, ranging from ∼32–95 min. The average starting time WBGT was 23.7 ± 2.4°C (range = 19.2–28.5°C). The flag warning categories for race start times over the 15 years included 4 yellow (26.7%), 10 red (66.7%), and 1 black (6.7%) (**Figure 1**). Start time flag warning categories provided a conservative estimate of conditions over the length of the race. In only 1 year (2010) did a flag category shift when considering the average exposure WBGT, and this involved a small decrease in WBGT that shifted the category from red (23.0°C) to yellow (22.6°C). Thus, we used the start time WBGT in additional analyses. The EHS rate per 1000 finishers was plotted against the start time WBGT (**Figure 2**). As the number of finishers were not available in 2012 and 2013, EHS rates were calculated for the remaining 13 years. We observed that EHS rates increased with increasing start time WBGT, with an $r^2 = 0.61$ ($p = 0.001$) (**Figure 2**).

Race Pace per WBGT Flag Color Warning

Average running paces for 243 EHS finishers were compared based on WBGT warning flag category (**Figure 3**). Faster EHS finishers has average race paces ranging from 3:09 to 3:21 min km^{-1} compared with average paces between of 5:15 to 5:34 min km^{-1} for slower EHS finishers. We found insufficient evidence to indicate a statistically significant difference in pacing among flag warning categories for either faster ($p = 0.555$) or slower runners ($p = 0.227$).

TABLE 1 | Finisher data and exertional heat stroke incidence and rate per 1,000 runners by year.

Year	Finishers	EHS cases	EHS rate
2003	8,058	37	4.59
2004	8,171	5	0.61
2005	7,532	19	2.52
2007	8,926	10	1.12
2008	8,743	15	1.72
2009	8,864	13	1.47
2010	9,653	6	0.62
2011	10,930	13	1.19
2012		11	
2013		15	
2014	11,060	17	1.54
2015	10,691	38	3.55
2016	10,381	16	1.54
2017	10,901	22	2.02
2018	11,063	10	0.90
Mean	9613.31	16.47	1.80
StDev	1289.74	9.66	1.16

EHS rates could not be computed for 2012 and 2013 because no finisher data were available.

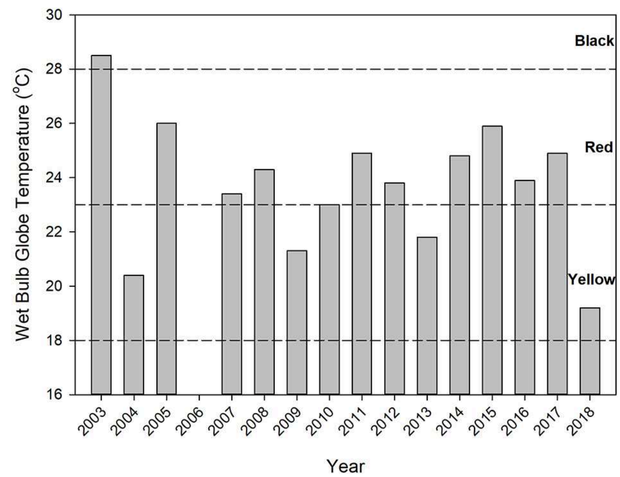

FIGURE 1 | Start time WBGTs and associated flag color warnings indicated by dashed horizontal lines. No finish times were available for EHS cases in 2006 and WBGT data were excluded from the study.

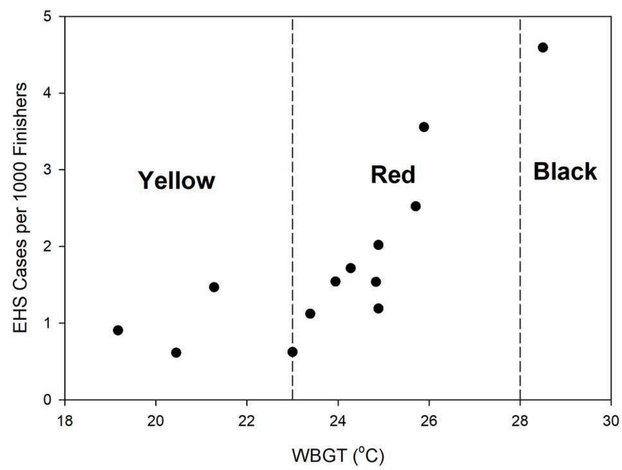

FIGURE 2 | Relationship between start time WBGT and EHS rate per 1000 finishers. IIRM warning flags for runners are categorized as low (green, <18°C), moderate (yellow, <18–23°C), high (red, 23–28°C), and extremely high (black, >28°C) risk for hyperthermia (Mears and Watson, 2015).

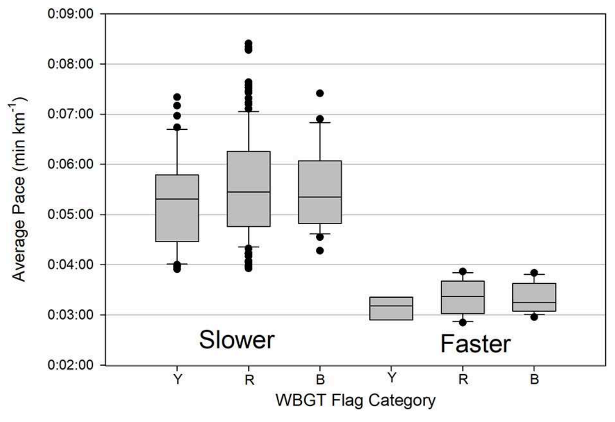

FIGURE 3 | Box and whisker plot of average race pacing among IIRM WBGT warning flag categories (Y is yellow, R is red, and B is black) for faster and slower EHS finishers. The dark line in the box is the median, the top and bottom of the box are 75 and 25 percentiles, respectively, the top and bottom lines are the 90th and 10th percentiles, respectively, and the circles represent outliers.

Race Finish Times for EHS Finishers vs. Overall Runner Population

The average running paces for both EHS and non-EHS finishers (elite and non-elite) were compared for the years 2014–2018. During this period, there were 53,369 non-EHS finishers and 100 EHS finishers (93 non-elite and 7 elite). There is a significant difference in average racing pacing between EHS and non-EHS runners, when controlling for age, gender, race performance (fast vs. slow), and starting time WBGT [$F_{(1,53,444)} = 44.120$, $p < 0.0001$). Indeed, the estimated marginal means indicates the average running pace was faster for EHS finishers (5:35 min km^{-1}) compared with non-EHS finishers (6:18 min km^{-1}).

DISCUSSION AND CONCLUSIONS

The purpose of this study was to identify if pacing played a role in the incidence of EHS at the New Balance Falmouth Road Race. This race provides an excellent case study because of the high rates of EHS compared with other road races (DeMartini et al., 2014). Thermoregulation during exercise in heat is influenced by the amount of metabolic heat produced and the amount of heat that is effectively dissipated through some combination of evaporation, radiation, convection, or conduction, depending on environmental conditions. Previously, DeMartini et al. (2014) examined the relationship between environmental conditions and the incidence of EHS. They reported greater incidence of EHS as the environmental condition become warmer. This outcome shows that the margin for amount of heat dissipation (i.e., allowed-heat dissipation) becomes narrower as the environmental condition becomes warmer, making it harder for runners to meet the heat dissipation required to maintain thermoregulation. Previous studies did not, however, address the role of race pacing among EHS runners, which is directly associated with the extent of metabolic heat produced by runners.

It has been speculated that the unusually high EHS rates at Falmouth are related to not only the warm conditions but also the high intensity and greater metabolic heat production produced in this shorter (11.26 km) race compared to longer marathons (DeMartini et al., 2014; Adams et al., 2016). The running speed has been strongly correlated with rises in core body temperatures (e.g., Noakes et al., 1991; Cheuvront and Haymes, 2001; Roberts, 2006) during races. Theoretically, runners should self-regulate their pacing strategy based on some combination of physiological feedback and previous experience (Tucker and Noakes, 2009). This often does happen as decrements in performance are observed in increasingly warm and hot conditions (e.g., Zhang et al., 1992; McCann and Adams, 1997; Ely et al., 2007). Roberts (2006) even observed an EHS suffered under mild weather conditions (ambient temperature 9.5°C) caused by the runner's fast pace in the last 16 km of a race, which suggests that sustained fast pace running can increase the relative risk of EHS even when the environmental conditions seem favorable from human heat balance standpoint. Our findings lend support to these conclusions. We observed that the average pace of EHS finishers was greater than non-EHS finishers, even when controlling for age, gender, race performance (elite or non-elite), and WBGT. A plausible explanation for this association is that having a faster average pace would result in relatively greater metabolic heat production and a greater chance of reaching the upper limit of thermoregulatory threshold that could increase the relative risk of EHS. Since etiology of EHS is multifactorial, we acknowledge that faster average pace alone would not induce elite or fitter individuals to collapse to EHS. However, because pacing is one of the few modifiable risk factors that these runners may consciously adjust at their own discretion, educational efforts should be made by race organizers to prevent overzealous runners from trying to achieve a goal finish time that is not safe at a given environmental condition.

Given that these runners competing at faster average paces may be at higher relative risk for EHS, mitigation measures should be attempted. In athletic settings, there are often external motivation and peer pressure (i.e., competition against teammates, desire to impress peer, a pre-set goal to achieve a personal best) that may push the athletes to continue exercise at an intensity that is unmatched to their physical fitness (Adams et al., 2016). Such external drive to sustain physical effort unmatched to fitness is one of the key risk factors of EHS (Rav-Acha et al., 2004). Although this is an inherent trait of any athlete who has a set goal, runners that participate in race events must first recognize and understand the importance of self-pacing and adjusting it accordingly to the environmental condition. At present, the Falmouth Road Race does not post start time WBGT values to provide guidance for runners. Informing runners of weather conditions to help guide them to optimizing their performance for safety might be a simple and cost-effective approach. One approach prior to the race would be to send informational e-mails to runners ahead of time to educate them about the risks of competing in hot weather. In addition, on race day the announcer could remind runners of the WBGT flag level and flags could be used at various distance markers to remind runners of heat hazards. Other races like the Boston Marathon use product like Everbridge (https://www.everbridge.com/) to push weather hazard warnings as text messages to cell phones.

This is a retrospective study that considered many years of data from the Falmouth Road Race. As such, we did not have detailed health information from race participants (e.g., fitness status, heat-acclimatization status, hydration, or pre-existing medical conditions) that may have influenced the risk for an EHS. A key limitation of our study, then, is that we can only provide an association between race pacing and EHS occurrence but not a cause and effect relationship. Even so, we provide a plausible mechanism linking pacing and EHS, and our findings lend support to the well-established practice of weather-based activity modification.

For future work, we hope to add morphological characteristics in our EHS risk stratification since the rate of metabolic heat production and dissipation is directly influenced by body mass and relative body surface area (Cramer and Jay, 2015). Furthermore, identifying barriers for adjusting race day strategy (i.e., race pace) by environmental condition will help us identify effective ways to disseminate safety information that can help modify runners' behavior during warm race.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Connecticut Institutional Review Board. Written informed consent from the participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

YH, AG, and DC conceived of the presented idea. AG, YH, DC, JJ, and RS contributed to the design and implementation of the research, to the analysis of the results, and to the writing of the manuscript.

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REVIEW
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How to Evaluate and Improve Foot Strength in Athletes: An Update

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The foot is a complex system with multiple degrees of freedom that play an essential role in running or sprinting. The intrinsic foot muscles (IFM) are the main local stabilizers of the foot and are part of the active and neural subsystems that constitute the foot core. These muscles lengthen eccentrically during the stance phase of running before shortening at the propulsion phase, as the arch recoils in parallel to the plantar fascia. They play a key role in supporting the medial longitudinal arch, providing flexibility, stability and shock absorption to the foot, whilst partially controlling pronation. Much of the foot rigidity in late stance has been attributed to the windlass mechanism – the dorsiflexion of the toes building tension up in the plantar aponeurosis and stiffening the foot. In addition, recent studies have shown that the IFM provide a necessary active contribution in late stance, in order to develop sufficient impedance in the metatarsal-phalangeal joints. This in turn facilitates the propulsive forces at push-off. These factors support the critical role of the foot in providing rigidity and an efficient lever at push-off. During running or sprinting, athletes need to generate and maintain the highest (linear) running velocity during a single effort in a sprinting lane. Acceleration and sprinting performance requires forces to be transmitted efficiently to the ground. It may be of particular interest to strengthen foot muscles to maintain and improve an optimal capacity to generate and absorb these forces. The current evidence supports multiple exercises to achieve higher strength in the foot, such as the "short foot exercise," doming, toes curl, towing exercises or the more dynamic hopping exercises, or even barefoot running. Their real impact on foot muscle strength remains unclear and data related to its assessment remains scarce, despite a recognized need for this, especially before and after a strengthening intervention. It would be optimal to be able to assess it. In this article, we aim to provide the track and field community with an updated review on the current modalities available for foot strength assessment and training. We present recommendations for the incorporation of foot muscles training for performance and injury prevention in track and field.

Keywords: intrinsic foot muscles, foot strengthening, assessment, track and field athletics, exercises

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INTRODUCTION

The foot is a complex joint system with multiple degrees of freedom that play an important role in athletic tasks such as running or sprinting. The compliance of the foot is remarkable and its spring-like properties—in the medial longitudinal arch (MLA) – allow mechanical energy to be stored and returned at each step (Ker et al., 1987). Previous studies have shown that this spring mechanism was provided by the elastic components of the plantar fascia or aponeurosis (PA). This may account for 8–17% of the mechanical energy required for a stride (Ker et al., 1987; Stearne et al., 2016) and it increases stiffness via the windlass mechanism. Recent studies showed however that this spring cannot simply be passive, as it cannot explain the ability of the foot to adapt to the mechanical loads of running or sprinting (Riddick et al., 2019). Kelly et al. (2018) showed during running that as speed increases, so does the dissipation of mechanical energy within the foot. This can be modulated by the muscular capacity of the intrinsic foot muscles (IFM).

The IFM are the main local stabilizers of the foot and are part of the active and neural subsystems that constitute the foot core (McKeon et al., 2015). With their anatomical insertions located under the foot, these muscles lengthen eccentrically during the early stance phase of running, producing negative work before they shorten during the late stance phase as the arch recoils to produce positive work (Fourchet and Gojanovic, 2016). This active contraction aids propulsion and is enabled by the following three muscle-tendon units: abductor hallucis (AbH), flexor digitorum brevis (FDB), and quadratus plantae (QP) (Kelly et al., 2015).

Because the IFM are usually neglected in assessment and treatment, a key component of foot core stability is not considered. We aim to provide the track and field community an updated review on the current modalities available for foot strength assessment and training. Running or sprinting is a cyclic activity involving all joints and muscles groups in the lower limbs, including the IFM, and the metatarsophalangeal (MTP) joint. We believe that it is of interest to assess the MTP joint's role during sprinting, especially looking at the link between midfoot and plantar flexors' torque before considering the various strengthening modalities and protocols. We will present recommendations for the incorporation of foot muscles training or performance and injury prevention in track and field.

THE FOREFOOT REGION AND RUNNING OR SPRINTING

During running or sprinting, athletes need to generate and maintain the highest (linear) running velocity during a single effort in a sprinting lane. Acceleration and sprinting performance requires forces to be transmitted efficiently to the ground. In particular, the production of horizontal force during the acceleration, more than vertical force, is related to sprinting performance. Indeed, the fastest runners at the end of the acceleration phase are not those who produce the highest total force, but those who manage to orient the forces horizontally (Morin and Samozino, 2016).

To achieve this, the sprinter must accomplish a series of segment rotations (Krell and Stefanyshyn, 2006) and gross moment generation about the lower limb joints, including hip, knee, and ankle (Tanaka et al., 2019). The small MTP joints (via dorsiflexion) may be related to sprint performance, as several studies have shown (Krell and Stefanyshyn, 2006; Bezodis et al., 2012). Stefanyshyn and Nigg (1997) investigated the energy patterns at the foot level during sprinting and found a large negative net energy balance (a lot of energy absorbed, whilst little produced) in the MTP joint during early to late stages of stance phase. These authors concluded that performance may be improved through a reduction in the energy loss at the MTP joint, but the question of how to achieve a better energy balance, hence better performance at push-off, remains. For example, Smith et al. (2014) found that varying the stiffness of spikes resulted in a significant decrease in MTP joint range of motion as well as dorsiflexion velocity when compared to barefoot. Spikes enable the MTP joint to plantar flex during push-off without affecting the windlass mechanism, which in turn facilitates propulsion by increasing the length of the moment arm (Smith et al., 2014).

This longer lever arm requires increased strength from the plantar flexors, and running athletes can benefit from it: a larger and more efficient horizontal force production may enhance performance (Morin and Samozino, 2016). A recent study showed that IFM activity in late stance is needed to generate sufficient impedance at the MTP joints, which in turn provides an efficient push-off (Farris et al., 2019).

Finally the MTP joint plays a key role during sprinting and that may result in the development of very strong foot muscles in sprinters population. However, Tanaka et al. (2019) demonstrated that although elite sprinters have thicker foot muscles compared with non-sprinters, AbH thickness correlates positively with their 100 m personal best. In other words a bigger AbH might be a negative factor for superior sprint performance. On the contrary, Yuasa et al. (2018) showed a significant correlation in collegiate American football players between maximal toe flexors strength with a dorsiflexed MTP and the ability to change direction in pro-agility and 3-cone tests. Abe et al. (2016) found in active subjects that fourth and fifth toe flexor strength was correlated positively with walking speed in men ($r = 0.584$) and women ($r = 0.553$), whereas Hashimoto and Sakuraba (2014) found that 8 weeks of toe flexors exercises decreased 50 m best personal time in 12 men.

Although toe flexors strength is generated by a simultaneous action of both intrinsic and extrinsic foot muscles, the IFM seem most likely to be the main contributors to MTP joints torque (Farris et al., 2019). Again, we should not underestimate the role of the MTP joints in strength training. In summary, strengthening interventions should not be limited to extrinsic foot and ankle muscles (e.g., flexor digitorum longus, triceps surae, flexor hallucis longus), but should also target intrinsic foot muscles.

THE MIDFOOT (MEDIAL) REGION AND RUNNING OR SPRINTING

The foot enjoys some flexibility characterized by the medial longitudinal arch (MLA) which compresses and recoils. This ability allows mechanical energy to be stored and then released sequentially with every running step. Previous studies have proposed that mobility of the MLA can partly enhance the triceps surae and longus flexor hallucis moment during the push-off (Leardini et al., 2007; Kelly et al., 2014). Fourchet et al. (2015) emphasized the important role of the MLA in transmission of force through the foot and as a load-absorbing structure in fatigued adolescent runners. This highlighted the reciprocal interaction between plantar flexors and MLA – a compliant MLA results in hyperpronation and this may impede force transmission through the foot at stance phase leading to early plantar flexor fatigue. This means that a more flexible midfoot does not really lock, and hence produces less power, inefficient force transfer through the foot lever and insufficient foot stiffness.

This relationship between MLA and plantar flexor torque has been shown in one study where hyperpronated feet showed lower concentric force of the plantar flexors when compared to neutral feet (Snook, 2001). These findings gave support to the following biomechanical theory: the lever angle of the Achilles tendon and the plantar flexors would at a disadvantage in hyperpronation, which leads some force produced by these muscles to be applied medially (no propulsive effect) rather than mostly upward (Fourchet, 2012). From a neurophysiological perspective, studies on electromyography (EMG) activity and pronation showed that hyperpronation may alter the function of foot and ankle muscles. Novacheck (1998) reported a delayed time to maximum pronation beyond 40% of stance in case of excessive pronation. This could be explained by the decreased activity of plantar flexors during fatigue: their supination effect is decreased and causes an increased load under the MLA. Fourchet et al. (2015) shown after high intensity running that plantar flexors display a reduced resistance to fatigue and an increase in relative load medially under the midfoot. We hypothesized that excessive foot pronation leads to fatigue of plantar flexor and points to the interdependence between plantar flexors and IFM, the latter being often difficult to turn on (Boon and Harper, 2003). We propose that there may be an interdependent coupling between plantar flexors and IFM, which is made biomechanically possible as plantar flexion moves the center of pressure forward and increases the load under the midfoot.

Finally, a stiff MLA seems to play a key role in ensuring a stable stance phase, and facilitating its load-absorbing task, the one which mitigates the dissipation of the mechanical energy produced by plantar flexors at push-off. Takahashi et al. (2016) demonstrated in walking that an increased foot stiffness (with shoes and orthotics) altered soleus muscle behavior, resulting in greater peak force and reduced fascicle shortening speed. Therefore, in addition to the optimization of spikes conception, implementing strengthening exercises of the intrinsic foot musculature with the aim to improve strength and stiffness of the MLA appears to be of high interest in athletes. This

FIGURE 1 | Measurement of the arch rigidity index.

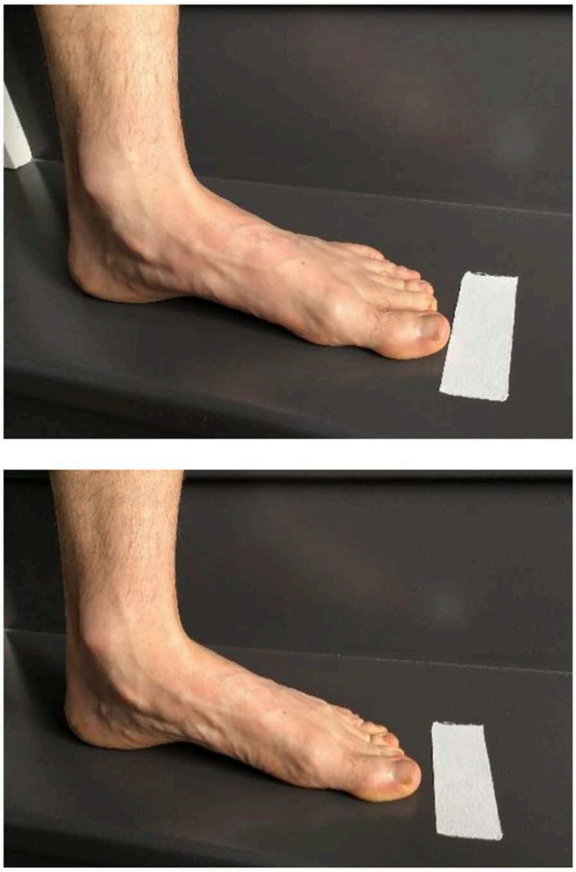

FIGURE 2 | Short foot exercise.

brings us to the necessity of specific and validated tests to assess such interventions.

TESTING FOOT STRENGTH

The assessment of foot muscle strength is addressed in the literature with magnetic resonance imaging (MRI) or ultrasound imaging (USI) (Soysa et al., 2012; Gooding et al., 2016; Ridge et al., 2018) in order to quantify muscle thickness or cross sectional area, but these modalities are expensive and not applicable on the field by coaches or athletic trainers. Numerous other affordable measurement methods are available and come with an interesting level of validity and reliability. We can mention the toe flexor strength with toe-dynamometry (Spink et al., 2010) and the paper grip test (De Win et al., 2002) and there are several indirect tests assessing the strength or stiffness through the deformation or mobility of the foot arches in weight bearing and non-weight bearing conditions. They are the medial arch height (Okamura et al., 2017), the arch rigidity index (Mulligan and Cook, 2013), the navicular drop (ND), and the foot mobility measurement (FMM) (McPoil et al., 2009), which we will describe in detail.

Medial Arch Height

This assessment performed during gait and/or standing phase requires the use of the Oxford Foot Model, a 3D multi-segment foot model with a good to excellent repeatability (Okamura et al., 2017). In this test, the MLA height is defined as the normal distance of the plane of the forefoot from the proximal first metatarsal marker by the Oxford Foot Model. The medial arch height can be measured before and after a strengthening programme or a fatiguing protocol for instance (Okamura et al., 2017).

Arch Rigidity Index

The arch rigidity index (ARI) is calculated by dividing the standing arch height index by the sitting arch height index and it represents the structural mobility of the MLA (Mulligan and Cook, 2013). An ARI close to 1 represents a stiffer MLA while increasing foot flexibility correlates with numbers that rise well above 1. The arch height index is calculated by dividing the height of the dorsum of the foot by the truncated length of the foot to obtain a ratio in both seated and standing positions (**Figure 1**). The truncated length is the distance from the most posterior aspect of the calcaneus to the center of the first metatarsal head, and the height of the dorsum of the foot can be measured with a modified carpenter's square with a bubble level arm at 50% of the total foot length.

Navicular Drop

The sit-to-stand double-leg or single-leg navicular drop test is the most popular evaluation of longitudinal arch stability in the literature. The athlete sits with his hips, knees, and ankles bent to 90° and the feet resting on the floor. The inferior border of the prominent tuberosity of the navicular bone is palpated and marked with a pen, and the distance to the ground is measured using a steel ruler (resolution: 0.5 mm). At this point the tester asks the athlete to stand barefoot on a 4-in (10.16 cm) box, full weight on the foot being measured, while the other foot rests lightly on the box (Cote et al., 2005). The difference between the two measures (sitting vs. standing) is the navicular drop. The tester must repeat three measures and the average value is recorded.

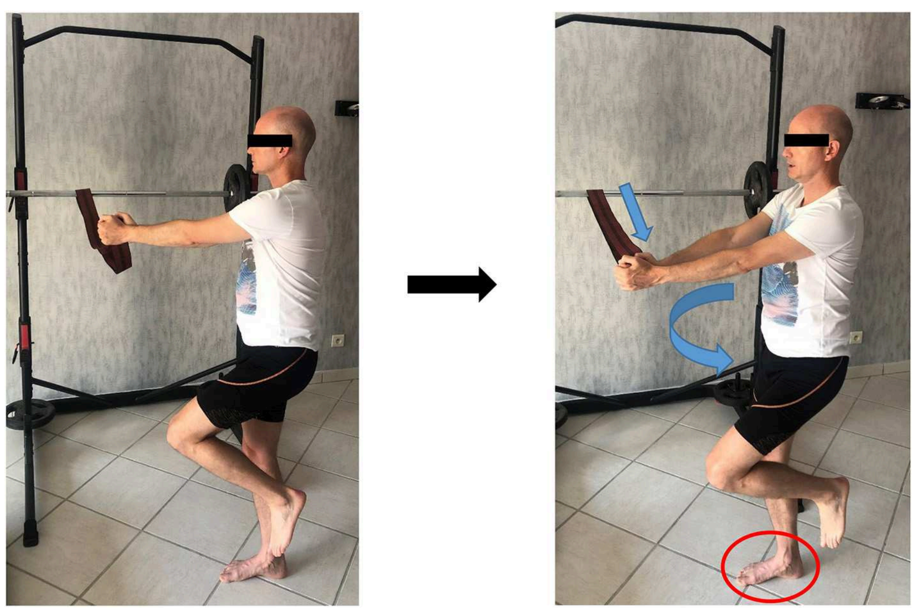

FIGURE 3 | Short foot exercise with cross-body inversion focus (with written informed consent obtained from the subject).

TABLE 1 | Summarizes the recent studies on the topic.

Authors	Population	Group exercises	Modalities	Results
Sulowska et al. (2019)	Long distance runners ($n = 47$)	Vele forward lean + Reverse tandem gait + Short foot exercise + ankle muscles strengthening for: neutral (group 1) and pronator (group 2)	6 weeks 30 min daily Progression (every 2 weeks): increasing load and level of difficulty and adding perturbation (tennis ball, a stability disc, and band loops)	↑ peak torque knee flexion (group 2) ↑ power in each 35 m run (group 2) ↓ 35 m run time (group 2)
Unver et al. (2019)	Pes planus ($n = 41$)	Short Foot Exercise (SFE) group Control group	6 weeks 2 times/week (supervision)/5 times/week (home) 5 s of contraction 3 sets of 15 repetitions Progression: sitting position (1 et 2), double (3 et 4) and single leg stance (5 et 6)	↓ Navicular Drop (ND), Foot Posture Index (FPI), Pain and Disability Score ↑ Plantar force at midfoot region
Fraser and Hertel (2018)	Healthy, recreationally active young adults ($n = 24$)	IFM exercises program: Hallux extension Lesser toe extension Toes-Spread-Out (TSO) SFE	4 weeks 3 times daily Completed a daily training log detailing the type, position, volume, and frequency of exercises performed. Home exercises were progressed if the task was performed adequately (no compensations, not too slow, and no obvious clumsiness).	↑ IFM activation ↓ perceived difficulty No significant (NS) effect on muscle activation
Taddei et al. (2018)	Healthy long distance runners ($n = 31$)	Foot and Ankle muscle strength training group Stretching group	8 weeks 2 times/week and then 3 times/week (8 weeks) and 1 year of follow-up 20–30 min (guided by software videos)	↑ cross sectional area (CSA) of AbH and FDB No effect on IFM strength Improvement for some foot kinematics parameters
Sudhakar et al. (2018)	Middle distance runners ($n = 30$)	Vele forward lean + Walking backward (Reverse tandem gait) for VFR group Plantar Short Foot (PSF) Exercises group: TSO + Plantar roll out exercises + Fine toe curl exercises and big toe curl exercises	4 weeks 5 times/week 15 min, 2 times/day Progression => Sitting position, standing position, half squat	↑ of Functional Movement Screen (FMS) compared to VRF group ↓ Foot posture index
Gooding et al. (2016)	Healthy subjects ($n = 8$)	Hallux extension Lesser toe extension Toe Spread Out (TSO) SFE	1 set of 40 repetitions	SFE ↑ activation of AbH (29.7%) and FDB (29.8%)
Kamonseki et al. (2016)	Plantar fasciitis ($n = 83$)	Foot exercise group Foot and Hip group Stretching alone exercise group	Foot exercise group: Toe curl exercise (3 sets of 15 reps): 1–2 kg SFE (3 times for 1 min)	All 3 exercise groups improve: Quality of life, pain, activities of daily living, sports & recreation
Kim and Kim (2016)	Flexible flat foot ($n = 14$)	SFE group Arch support insoles group	30 min per day 3 times/week during 5 weeks	↑ Y Balance test (both group) ↓ Navicular drop (SFE group)
Sulowska et al. (2016)	Long distance runners ($n = 25$)	Vele forward lean + Reverse tandem gait + SFE	6 weeks Daily basis for 30 min Progression: sitting, standing, half-squat	↓ FPI: item 1 et item 3 ↑ FMS (deep squat, active straight leg raise)
Kim et al. (2015)	Mild and moderate hallux valgus ($n = 12$)	Toe spread out + Orthosis	20 min/days during 8 weeks 4 times per week	↓ hallux valgus angle (HVA) + HVA during active abduction ↑ CSA AbH

(Continued)

TABLE 1 | Continued

Authors	Population	Group exercises	Modalities	Results
Panichawit et al. (2015)	Flexible flat foot ($n = 5$)	Calf muscles stretching exercise, strengthening of the tibialis posterior (TP), Peroneus Longus (PL), Flexor Digitorum Longus (FDL), ankle dorsiflexion, and IFM as well as co-contraction of the invertors and evertors muscles	Stretching: 10 reps Strengthening: 10–15 reps (3 sets) Progression: resistive exercises with added bands	↑ TP and PL strength ↓ Foot function score NS difference in plantar contact area and plantar peak pressure
Hashimoto and Sakuraba (2014)	Healthy male subjects ($n = 12$)	Toe flexor strength	8 weeks 200 reps/day, 3 times per week Load (3 kg -> 10 kg)	↑ vertical jump height + 50 m dash performance + IFM strength + 1 legged long jump ↓ arch length
Moon et al. (2014)	Hyperpronated feet ($n = 18$)	SFE	1 session: 5 sets of 3 reps × 5 (2 min rest) with 5 s of contraction	↑ dynamic balance
Goldmann et al. (2013)	Healthy subjects ($n = 15$)	Toe flexor strength	7 weeks (560 contractions) 90% of maximal voluntary isometric contraction	↑ toe strength ↑ horizontal jump distance ↑ external MTP joint dorsiflexion moments ↑ MTP plantar flexion moment
Kim et al. (2013)	Mild hallux valgus ($n = 25$)	TSO group SFE group	Practice for 2 weeks SFE and TSO exercises were conducted for 15 min once per day On the day of the experiment, subjects performed the SFE and TSO exercises 5 times for familiarization with both exercises.	TSO exercise showed significantly greater activation of the AbdH than did SFE ↑ ratio of AbdH to AddH muscle activity significantly higher in TSO group Significantly Greater angle of the first MTP joint in horizontal plane during TSO than SFE
Mulligan and Cook (2013)	Healthy subjects ($n = 21$)	SFE	4 weeks 3 min/day 30 reps (5 s of contraction) Progression: sitting to double and single leg stance + perturbations (through instability or vision)	↓ navicular drop ↑ Arch height index Improvement in balance and reach task
Lynn et al. (2012)	Healthy subjects ($n = 24$)	SFE group Tower curl group	4 weeks 100 reps/day 5 s of contraction Progression: sitting (week 1 and 2), standing (week 3 and 4)	NS difference in navicular height or static balance test ↓ Medio-lateral center of pressure movement in dynamic balance test (SFE > for non-dominant limb)
Jung et al. (2011b)	Pes planus ($n = 28$)	Foot orthosis + SFE group Orthosis group	8 weeks 3 sets of 15 reps (2 times/week): hold the position for 5 s with 2 min rest periods between sets Progression: increased up to 5 reps and then in the next progression, the holding time increased to 10 seconds	↑ CSA AbH in foot orthosis + SFE group ↑ flexor hallucis strength in SFE + Orthosis group
Jung et al. (2011a)	Normal feet ($n = 20$)	SFE group Tower curl group	SFE or Tower curl in maximal contraction (3 trials of 5 s => muscular activation) 15 min/day during 2 weeks Progression: sitting and standing on single leg	↑ AbH activity in SFE group in comparison to Tower curl group

Foot Mobility Measurement

The foot mobility measurement is a composite measure of vertical and medial to lateral mobility of the midfoot, whereas ND assess only vertical mobility. It has been described as a relevant technique for the assessment of foot mobility differences between non-weight bearing and weight bearing positions (McPoil et al., 2009).

To measure the FMM, three instruments are needed: weight bearing and non-weight bearing arch height gauges and a device to measure midfoot width, both of which can be relatively easily manufactured, with the inclusion of a digital caliper (**Figure 1**). Refer to McPoil et al. (2009) for a full description of the method. The athlete stands on a foot measurement platform (heels placed in heel cups) in order to measure dorsal arch height and midfoot width in bipodal weight bearing. Then, the same non-weight bearing measurements are recorded with the athlete sitting, both legs hanging in a perpendicular relaxed position. The procedure used for the weight bearing measures is then repeated. A method based on the Pythagorean Theorem is used to calculate the FMM:

$$\text{FMM} = \sqrt{(DiffAH)^2 + (\text{DiffMFW})^2} \quad (1)$$

where "Diff AH" and "Diff MFW" are the changes in dorsal arch height and in midfoot width between weight bearing and non-weight bearing, respectively.

FOOT STRENGTHENING STRATEGIES

Strengthening of the foot muscles responds to the same training principles as any other muscle group. IFM strengthening can be performed in isometric, concentric, eccentric or plyometric modes.

Isometric Strengthening: Short Foot Exercise, Toe-Posture Exercises, and Tower Curl

In isometric strengthening of the IFM, the most recognized exercise is the short foot exercise (SFE) (McKeon and Fourchet, 2015), where volitional control of the intrinsic foot muscles elevates the foot arches and shortens the foot. This is described as part of the foot core paradigm introduced by McKeon et al. (2015). The SFE is typically challenging to teach and learn, so that three gradual training steps have been recommended: (1) passive mode, (2) active-assisted mode, and (3) active mode. In passive mode, the athlete's foot is moved by the therapist or the coach through the short foot movement, allowing the athlete to feel, learn, and integrate the different positions. In the active-assisted

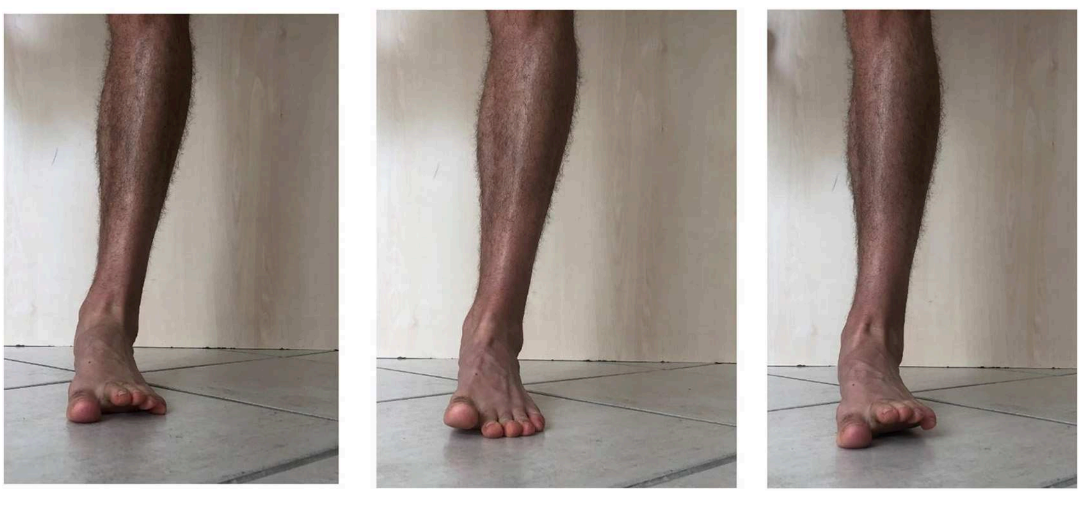

FIGURE 4 | Toe spread out exercise, 1st toe extension and 2nd to 5th toe extension.

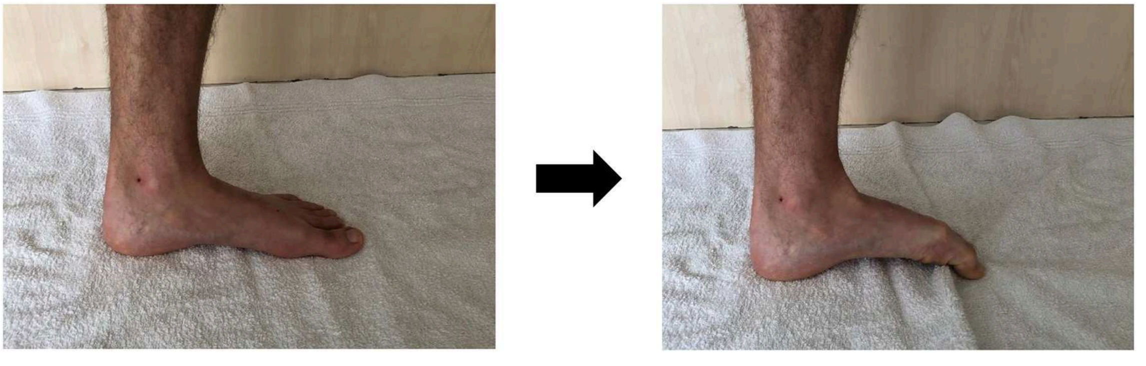

FIGURE 5 | Tower curl (Toe flexor exercise).

mode, active contractions of the plantar IFM are added to actively obtain the short foot position. Finally the active mode consists in the athlete performing the exercise without assistance (**Figure 2**).

It is also possible to combine the SFE with active and resisted activities of the upper body in order to create a cross-body inversion focus (i.e., trunk and pelvis medial rotation) and promote muscular chains facilitations (**Figure 3**).

It is worth mentioning that numerous others exercises commonly referred to as "toe yoga" or "toe posture exercises" have been shown to activate the IFM in a isometric contraction (**Table 1**). For example, the Toe-Spread-Out exercise (TSO), First To Fifth toe extension exercises are validated by Gooding et al. (2016). The TSO is carried out by a sequential extension of all toes, followed by hallux abduction, hallux flexion, and fifth toe flexion (**Figure 4**).

The "First-Toe Extension" or "Hallux-Extension" exercise is performed by extending the first metatarsophalangeal joint while maintaining the lesser toes (Second To Fifth) in contact with the floor (**Figure 4**). The "Second- To Fifth-Toes Extension" or "Lesser-Toes-Extension" exercise consists in extension of toes 2–5 whilst maintaining the hallux in contact with the ground (**Figure 4**).

We have stressed the importance of the MTP joint for sprint performance and some MTP strength exercises can be discussed.

FIGURE 6 | Short foot exercise in rotation (with written informed consent obtained from the subject).

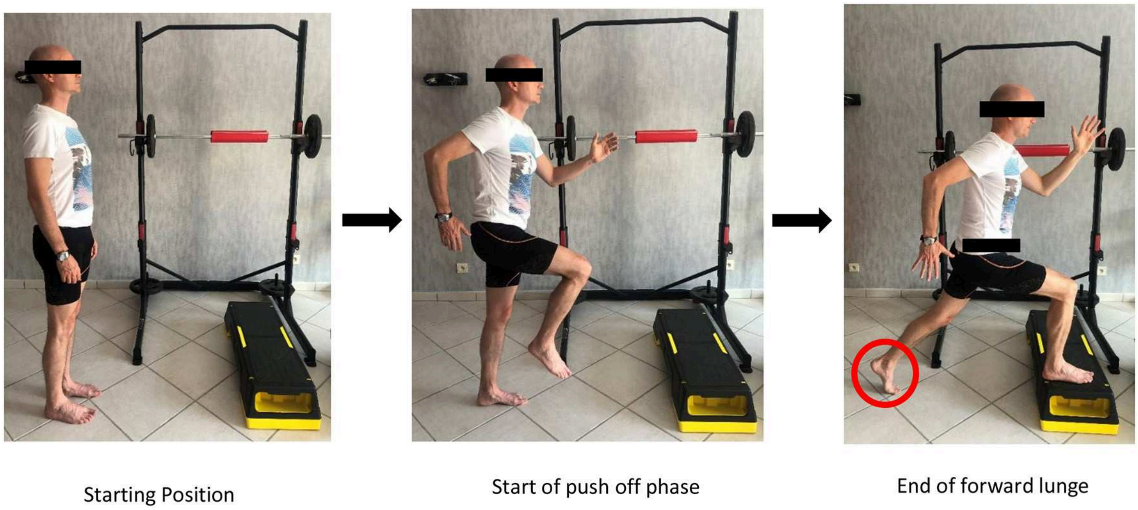

FIGURE 7 | Short foot exercise during propulsion (with written informed consent obtained from the subject).

Previously used techniques that attempted to strengthen the IFM involved toe-flexion exercises (Hashimoto and Sakuraba, 2014) but it seems that these exercises recruit more of the extrinsic foot musculature (such as the flexor digitorum longus) and make these muscles dominant over the IFM (Lynn et al., 2012). Hashimoto and Sakuraba (2014) developed a strength training program that focused on IFM strength by excluding the extrinsic muscles as much as possible by bringing the ankle in plantar flexion. The "Towel curl exercise" or "toe flexor strength" is performed in sitting or standing position with or without added weights, where the subject is asked to slowly curl the toes and fold the towel or dynamometer under the foot by flexing the toes [interphalangeal (IP) and metatarsophalangeal (MTP) flexion] (**Figure 5**). This type of exercises permits also to work the horizontal strength product by the IFM with the help of the extrinsic foot muscles.

Dynamic and Plyometric Foot Strengthening

From a biomechanical perspective, isometric exercises are not reflective of how foot muscles work during locomotion (Farris et al., 2019). The magnitude of load at the midfoot during running or even walking is so high that it is not possible for the foot muscles to generate sufficient force with low load tasks like the SFE. We suggest to progress from isometric to plyometric exercises in order to get closer to the specific function of running. We can consider heel rises or any exercises shifting the CoP in front of the body, as these will likely impose a much higher load on the midfoot (**Figures 6**, **7**).

Minimalist or Barefoot Running

The literature on the effects of running on foot muscular adaptations is relatively scarce and somewhat contradictory. Nevertheless, it does suggest that running could improve the cross-sectional area and the volume of foot muscles, and that this may be modulated by running mileage and experience (Miller et al., 2014; Johnson et al., 2015; Chen et al., 2016; Ridge et al., 2018). Based on the limited evidence available, there seems to be a positive effect of running on intrinsic muscle strength and size (Garofolini and Taylor, 2019). We will review some of these studies briefly.

Johnson et al. (2015) found that 10 weeks of training in minimal running shoes may be effective in increasing muscle size, especially abductor hallucis cross-sectional area. Chen et al. (2016) found that a 6-months transitioning running program to minimal shoes led to larger IFM. It is worth mentioning that a strengthening program was added in this protocol, and it is not possible to say which component was responsible for the observed changes in muscle volume (Chen et al., 2016). Similarly, after a 12 weeks transitioning programme, a significant improvement was reported in the volume and the cross-sectional area of the abductor digiti minimi in recreational runners (Miller et al., 2014).

Neuromuscular Electrical Stimulation (NMES)

An additional modality for the volitional strengthening of foot muscles is neuromuscular electrical stimulation (NMES) of the IFM. The aim is to strengthen the foot lever as the first interface between the ground and the athlete (Fourchet and Gojanovic, 2016). The incorporation of this modality has been shown to improve foot postural control and plantar pressure distribution in runners (Fourchet et al., 2009, 2011).

Scientific findings suggest that using NMES on foot muscles can decrease navicular drop after a 3-weeks programme (three sessions a week). In another study, we showed that combining NMES with other exercises during 5 weeks shifted plantar foot pressure distribution laterally, which resulted in a reduction of loads under the medial midfoot during running (Fourchet et al., 2009, 2011).

FIGURE 8 | Placement of electrodes for NMES on medial arch intrinsic foot muscles (McKeon and Fourchet, 2015).

Practically speaking, the set-up is very simple: the athlete stands with feet on the ground whilst the stimulator delivers NEMS as for 15 min, and a total of ∼75 contractions completed per training session. The two electrodes are placed behind the head of the first metatarsal to stimulate the medial arch intrinsic muscles (**Figure 8**). Biphasic symmetric regular-wave pulsed currents (85 Hz) lasting 400 ms are delivered, and each tetanic stimulation is delivered for 4 s, followed by an active rest period lasting 8 s (McKeon and Fourchet, 2015).

We recommend that the athletes performs an average of 9 to 12 NMES sessions through 3–5 weeks, as this will bring effective improvements. The athlete begins in bipodal stance during the first sessions and then progresses to single-leg stance and plyometric activities such as hopping.

CONCLUSION

The biomechanical specificities at the forefoot and the midfoot regions during running or sprinting require a high level of strength from the small foot muscles. The foot core system must act as a strong and rigid lever in order to best transfer lower limbs forces during propulsion, and it must also cope with significant amounts of constraints at the absorption phase, in the sense of impact attenuation.

The existing medical and scientific literature can help coaches and athletes to set up the most adapted exercises in order to strengthen their feet: variation and progression is necessary and ranges from isometric, concentric to eccentric contraction modes, from analytic to functional exercises, from volitional to electrically-assisted (NMES).

In order to track foot strength development and response to training, the athletic community can rely on several reliable and field-friendly assessments modalities.

This paper discusses aspects that are more performance-oriented or training-oriented, but the readers should keep in mind that the optimal control of the foot at stance phase is essential for the athlete's health as well. Overuse injuries linked to the control of the arch of the foot may be related to deficits in active foot stabilization during running, which may lead to increased tissue stresses. Medial tibial stress syndrome or Achilles tendinopathy are often linked to a lack of stiffness in the medial arch of the foot and its ability to cope with the changing demands for dynamic foot control.

We fully acknowledge that expert track and field coaches already apply a large body of the knowledge described in this article in their daily work with athletes. We do believe that for optimal health and performance outcomes, a close collaboration between coaches, sport scientists and medical staff is of primary interest and enables all parties to keep learning from each other.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Racing Fast and Slow: Defining the Tactical Behavior That Differentiates Medalists in Elite Men's 1,500 m Championship Racing

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Background: 1,500 m running has long been a blue ribbon event of track championship racing. The eventual medalists employ common tactical behaviors such as a fast sustained pace from the start (gun-to-tape), or, slow initial laps that precede a precisely timed race kick. Before the kick, there are positional changes caused by surging, that can go uncharacterized. The inter-relationship of surge events, tactical positioning, and kick execution may have important implications for eventual medal winning outcomes and require further definition.

Methods: In a randomized order, three middle-distance running experts were provided publically available video (YouTube) of 16 men's 1,500 m championship races across, European, World and Olympic championships. Each expert determined the occurrence of surges (defined as any point in the 1,500 m after the first 300 m where an athlete repositions by ≥3 places; or noticeably dictates a raise in the pace from the front) and the race kick. Following a second level verification of expert observations, tactical behaviors (quantity and distance marker within each race) mean distance from the finish were compared between fast (≤3:34.00, $n = 5$), medium (>3:34.00–≤3:41.99, $n = 7$) and slow (≥3:42.00, $n = 4$) race categories.

Results: Before the race kick, there were more surges in slow (5 ± 1.7, mean ±90% confidence limits) vs. fast races (1 ± 0.4, very large difference, *very likely*). The final surge before the race kick occurred earlier in fast (704 ± 133 m from the finish) vs. medium (427 ± 83 m, large difference, *most likely*), and slow races (370 ± 137 m, large difference, *most likely*). At initiation of the race kick in fast races, large positional differences were found between eventual gold (2 ± 1.2; *likely*) and silver (2.2 ± 1.6; *likely*) vs. bronze medalists (4.4 ± 1.2). In slow races, positional differences were *unclear* between eventual gold (4.3 ± 4.7), silver (4.8 ± 4.8) and bronze medalists (5.3 ± 1.5). Regardless of category, the race kick occurred on the last lap, with *unclear* differences between fast 244 ± 92 m medium 243 ± 56 m and slow 236 ± 142 m races.

Conclusions: Presenting tactical behaviors by race categorization (slow, medium, fast race times), provides a novel understanding of the nuance of racing tactics. The present findings highlight the importance of considering within race athlete decision making across multiple-race scenarios during championship preparation.

Keywords: performance, middle-distance running speed, coaching, tactics, strategy

INTRODUCTION

It is well-established across the middle-distance running literature that the final surge, more commonly known as the finishing kick, differentiates medalists in championship racing of the 1,500 m (Thiel et al., 2012; Mytton et al., 2015; Aragón et al., 2016; Casado and Renfree, 2018; Hanley et al., 2018). 1,500 m championship racing is akin to a game of chess, whereby an athlete must jostle for a favorable tactical position, ready to execute the "kick" at the opportune moment.

The current literature, whilst highlighting the concept of the "race kick" in the 1,500 m, is limited in methodology in several areas. Firstly, jostling for position in the early phases of the race is often overlooked and may require an element of surging that has bioenergetic consequences on an athlete's ability to kick (Fukuba and Whipp, 1999; Jones and Whipp, 2002). Importantly, these mid-race surges before the kick (i.e., up to and including the final surge), position the athlete to strike and are a critical piece of tactical execution (Hanley et al., 2018). Secondly, tactical assessments in the literature are often limited to analysis between intermediate race position and the probability of qualifying/progressing through rounds, as identified from sector splits (commonly only to 100 or 200 m sectors) (Renfree et al., 2014; Mytton et al., 2015; Casado and Renfree, 2018; Hanley et al., 2018). Whilst splits and subsequent velocity profiles are useful for general race characterization, an athlete's intermediate tactical position in relation to surges or the "kick" may occur between the resolution of the venues timing splits. With sports federation funding primarily determined by medal outcomes, providing further resolution on the medalists underpinning tactical behavior is of critical performance interest for coaches, athletes and sport performance staff.

Current literature on "the kick" in the 1,500 m is typically assessed from a one off championship (Renfree et al., 2014; Casado and Renfree, 2018), or in cases assessing multiple championships, an assumption is made that finals of varying finish time, whether that be fast, medium, or slow, result in the similar tactical execution (Mytton et al., 2015; Hanley et al., 2018). This assumption may be a misrepresentative interpretation of the tactical behavior required to win across a broad set of tactical scenarios. Athletes must be prepared for all eventualities on race day, which could range from gun-to-tape to sit and kick style racing (Fukuba and Whipp, 1999; Jones and Whipp, 2002). For example, the 2016 Rio de Janeiro Olympics men's 1,500 m final finish time was noted as "slow" (3:50.00) whereas the 2017 London World Championship was won in a markedly "faster" time (3:33.61). Thus, it is imperative for tactical positioning throughout the 1,500 m to be assessed with these different "fast," "medium," and "slow" pace categories in mind, and consider differences in bioenergetic demand and effort distribution. Ultimately, the difference in strategies required and the implications for coach and athlete preparation, training and race execution may be substantial.

Therefore, the current study aimed to answer the following questions in male 1,500 m races across European, Olympic and World Championships, between 2000 and 2017: (i), at what distance from the finish are race surges and the race finishing kick initiated and where were the eventual medalists positioned at these key points in the race? (ii), how do these outcomes differ in fast, medium, and slow pace race categories?

METHODS

The tactical positioning of men's 1,500 m medalists during surges and the kick was assessed using readily available footage from YouTube of the following elite athletics championships where medals are the priority, not finishing times or seasons best time: European Championships 2012, 2014, 2016, World Championships 2001, 2003, 2007, 2009, 2011, 2013, 2015, 2017, and Olympic Games 2000, 2004, 2008, 2012, 2016.

The term "kick" may be looked at from two perspectives. First, in reference to the "race kick" which globally characterizes the kick event within the race, defined herein as, "a one-time landmark moment in the race where the first athlete makes the races' first decisive and final break from the pace as a sustained pursuit for the finish line." Furthermore, there will be other athletes who execute their kick after this point (i.e., when each individual decides to utilize their remaining energetic resources), these are tactical responses to the first athlete who initiated the race kick (Renfree et al., 2015; Hettinga et al., 2017; Konings and Hettinga, 2018), thus these instances will be referred to herein as the "athlete kick." For clarity, the race kick will be the emphasis of the present investigation, with the athlete kick definition provided as a basis for clarity of interpretation, and opportunity for future investigation. Race surges often go uncharacterized, therefore, we herein defined in-race surges as "any point in the 1,500 m after the first 300 m where an athlete repositions by $\geq$3 places; or noticeably dictates a raise in the pace from the front (i.e., they are in the first 3 places)".

To overcome the limitation of 100 m sector resolution on tactical behaviors in previous studies, three independent middle-distance experts (12–20 years' experience working in the sport) analyzed the 16 race videos in a randomized order (Altman and Bland, 1999), following a familiarization trial of a race not included in the study ($n = 1$). To identify the medalists (top

3 finishers), experts were provided with the name, nationality, finishing position, finishing time, bib number and singlet color of each athlete. For each race, experts recorded the following: (a) the distance from the finish line that surges (i.e., total count) and the race kick were deemed to occur [sometimes this was not a medalist and were requested to give their expert judgement to the nearest 10 m)]; (b) the position (1st, 3rd, 5th etc.) of the eventual medalists during the respective surges and the race kick in (a). When athletes were side by side, the person on the inside rail was deemed in the higher position as running one lap in lane 2 adds 7 m extra race distance (Jones and Whipp, 2002).

Experts were instructed to watch videos without commentary, and permitted to stop or replay the video as often as required to accurately provide their observations. In addition, experts were asked not to look at online results of the race (IAAF website etc.) until after they had watched the race and finalized their answers. Once the expert results were collected, the primary and third author provided further verification. Whereby, no additional surges were introduced, but observations of experts on specific surge or race kick distances from the finish were confirmed using track landmarks (e.g., the 400 m finish line).

Races were characterized with the following rationale: "Fast pace" defined as race finishing times ≤3:34.00 ($n = 5$). Whereby, in the last 5 years <20 athletes per year have run faster than 3:34.00 from any nation. With a field allocation of 12 athletes in an IAAF World Championships or Olympic final, 3:34 was chosen as a pace that would be deemed fast by all eventual finalists. "Medium pace" (3:34.01–3:41.99) was selected as 3:41.99 is the United States of America Track and Field Trial "B" standard to compete at their National Championships ($n = 7$) and "Slow pace" were times ≥3:42.00 ($n = 4$).

ANALYSIS

Data are presented as means and 90% confidence limits (CL) unless otherwise stated. Mean differences in distance from the finish (m) and tactical position of the medalists at initiation of surges and the race kick, alongside number of surges before the race kick were assessed between fast, medium and slow pace races using magnitude based inferences (Hopkins et al., 2009). Comparison between means were calculated using a spreadsheet (Hopkins, 2007). The threshold values for effect size (ES) statistics were ≤0.2, trivial if there is overlap of 90% CL on positive or negative effect) or unclear (if 90% CL overlaps both positive and negative effect), ≥0.2 (small), >0.6 (moderate), >1.2 (large), and >2.0 (very large) (Batterham and Hopkins, 2006). The smallest worthwhile change was calculated as the standard deviation of the variable "e.g., Tactical position at the race kick for all race categories," multiplied by the ES. Probabilities were used to make a qualitative probabilistic inference about the true differences. The scale for interpretation was: <0.5%, most unlikely, almost certainly not; 0.5–5%, very unlikely; 5–25%, unlikely, probably not; 25–75%, possibly; 75–95%, likely, probably; 95–99.5%, very likely; >99.5%, most likely, almost certainly (Hopkins et al., 2009).

TABLE 1 | Men's 1,500 m championship race finishing times in their slow, medium, and fast categories.

Pace category	Event	Year	Winning time (m:ss.ss)
"Fast"	WC (London)	2017	3:33.61
	OG (Beijing)	2008	3:32.94
	WC (Paris)	2003	3:31.77
	WC (Edmonton)	2001	3:31.68
	OG (Sydney)	2000	3:32.07
Mean ± CL			**3:32.21 ± 0:01.65**
"Medium"	WC (Beijing)	2015	3:34.40
	WC (Moscow)	2013	3:36.28
	OG (London)	2012	3:34.08
	WC (Daegu)	2011	3:35.69
	WC (Berlin)	2009	3:35.93
	WC (Osaka)	2007	3:34.77
	OG (Athens)	2004	3:34.18
Mean ± CL			**3:35.05 ± 0:01.12**
"Slow"	OG (Rio de Janeiro)	2016	3:50.00
	EC (Amsterdam)	2016	3:46.65
	EC (Zurich)	2014	3:45.60
	EC (Helsinki)	2012	3:46.20
Mean ± CL			**3:47.11 ± 0:03.24**

WC, IAAF world championships; OG, olympic games; EC, European athletics championships; Fast, ≤3:34.00; Medium, 3:34.00–3:41.99; Slow, ≥3:42.00.

RESULTS

Mean and individual finish times for fast ($n = 5$), medium ($n = 7$), and slow ($n = 4$) categories are shown in **Table 1**. Before the race kick, there were more surges in slow (5 ± 1.7) vs. fast races (1 ± 0.4, very large difference, *very likely*). There were more surges in both slow vs. medium races (1.4 ± 1.7 moderate difference, *possibly*) and medium vs. fast races (2.4 ± 0.5 large difference, *very likely*), all **Figure 1**. The final surge before the kick occurred substantially earlier in a fast paced 1,500 m (704 ± 133 m from the finish) compared to medium (427 ± 83 m, large difference, *most likely*), and slow 1,500 m races (370 ± 137 m, large difference, *most likely*), as shown in **Figure 2**. Regardless of race category examined, the race kick occurred within the last 400 m (**Figure 2**), with *unclear* differences between race kick distance from the finish in the slow 236 ± 142 m, medium 243 ± 56 m and fast 244 ± 92 m races.

At initiation of the race kick, eventual medalists were in higher race positions in fast races (top 3 ± 1.2), than in slow paced races (top 5 ± 2.3, moderate difference, *possibly*). Specifically, within fast races, there was a large difference (*likely)* in the tactical position of the eventual gold (2 ± 1.2) and silver (2.2 ± 1.6) medalists vs. the eventual bronze medalist (4.4 ± 1.3), see **Figure 3A**. In medium pace races (**Figure 3B**), there were *unclear* differences in the tactical position of eventual gold (3.6 ± 2.4) and silver medalist (3.1 ± 2.2), however eventual bronze medalists (5.6 ± 1.6) were in lower positions at the race kick than silver (moderate difference; *likely*), and gold medalists (moderate difference; *possibly*). Across slow races (**Figure 3C**), there were *unclear* differences in the tactical position at initiation of the race

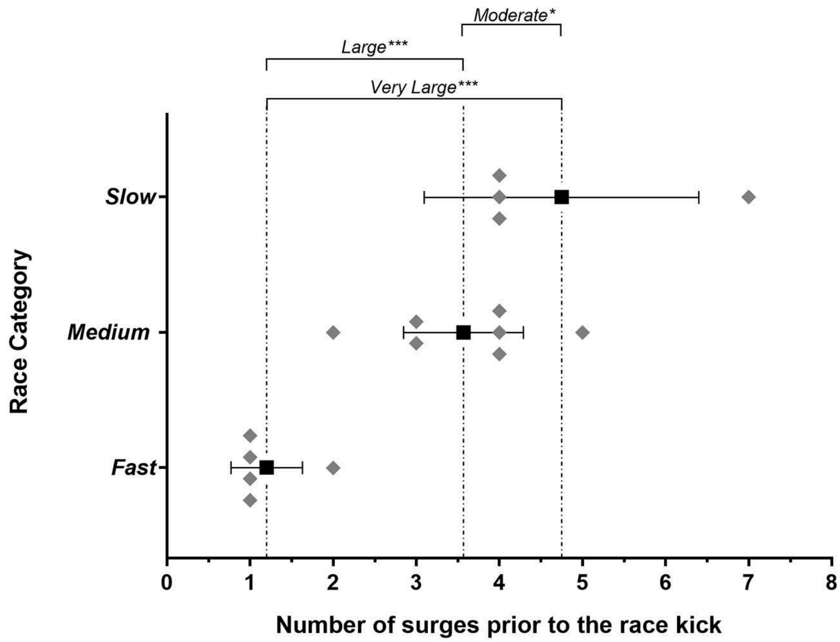

FIGURE 1 | Number of surges before the race kick within each individual *fast* ($n = 5$), *medium* ($n = 7$), and *slow* ($n = 4$) race analyzed, and the mean (90% CL) for each category in the solid square plots. Brackets indicate the magnitude differences between means of each of the three race categories with the probability of each difference indicated as *possibly substantial difference, **likely substantial difference, ***very likely substantial difference, and ****most likely substantial difference.

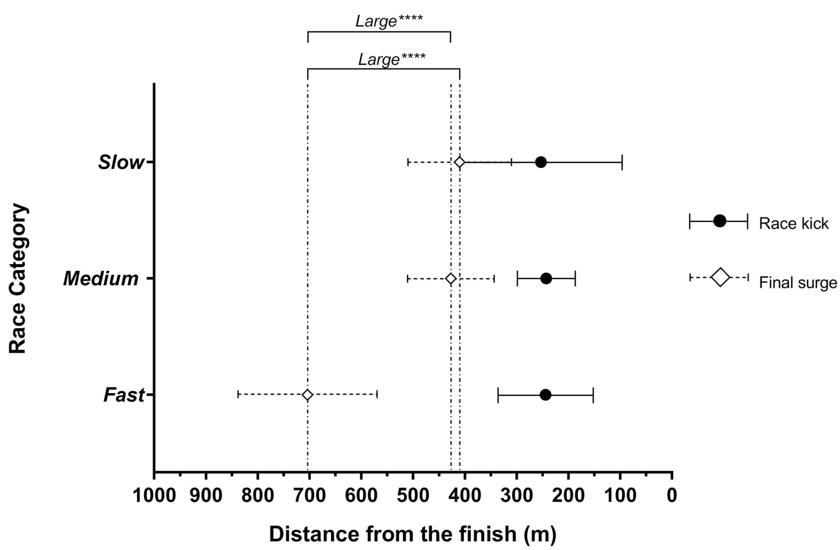

FIGURE 2 | Mean distance from the finish line of the reported final surge and race kick across fast ($n = 5$), medium ($n = 7$), and slow ($n = 4$) race categories. Brackets indicate the substantial magnitude differences between means of each final surge across the three race categories. The probability of each difference is indicated as *possibly substantial difference, **likely substantial difference, ***very likely substantial difference, and ****most likely substantial difference. Unmarked comparisons showed unclear differences. Error bars represent the 90% confidence limits.

kick between eventual gold (4.3 ± 4.7), silver (4.8 ± 4.8) and bronze medalists (5.3 ± 1.5).

DISCUSSION

The present study is the first in elite male 1,500 m runners to report the concurrent tactical positioning of eventual medalists alongside surge events and the race kick using a novel methods approach of fast, medium, and slow race category analysis. It revealed that substantially different tactical approaches are undertaken in different paced championship races. Specifically, on average more surges occur before the race kick in slow races, compared to fast and medium races (**Figure 1**). Surge events are most variable between slow races (**Figure 1**), and

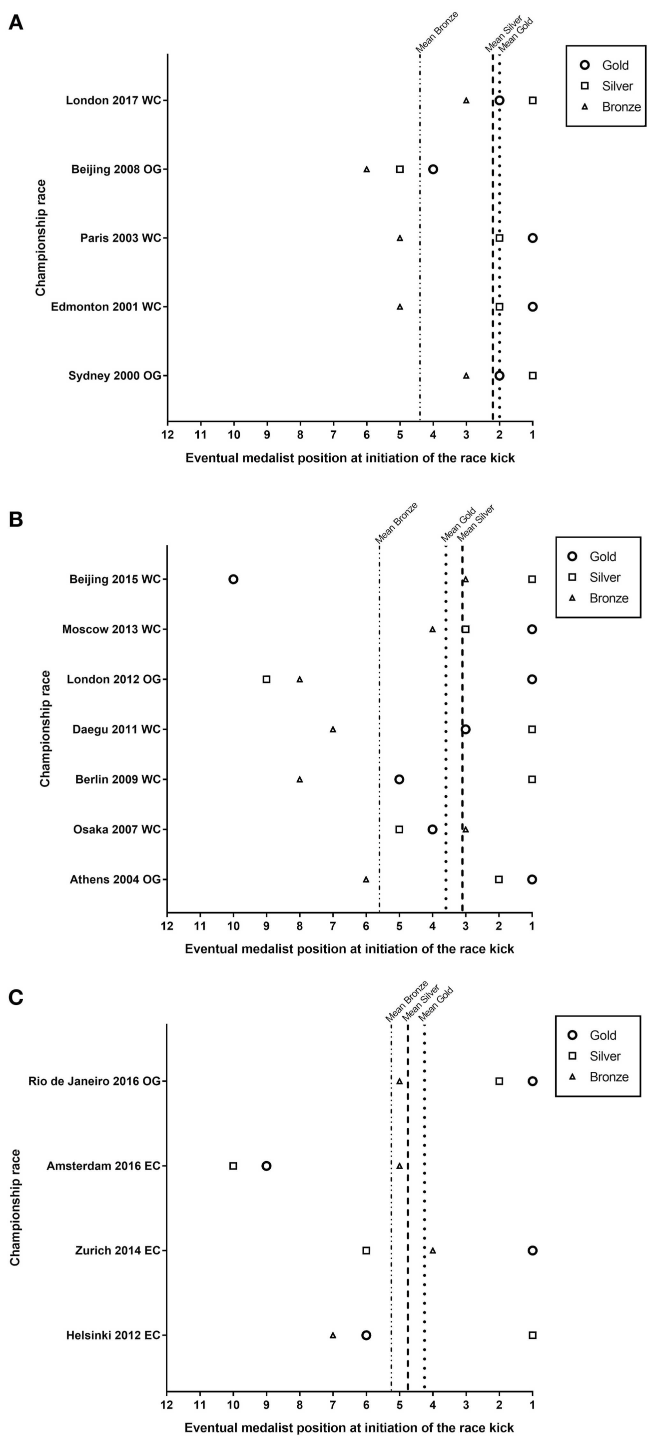

FIGURE 3 | Positions of all eventual medalists at the initiation of the race kick in each individual race from the fast **(A)**, medium **(B)**, and slow **(C)** race categories. WC, IAAF world championships; OG, olympic games; EC, European athletics championships.

the final surge before the race kick occurs substantially earlier in fast vs. medium and slow races (**Figure 2**). Consistent with previous observations (Thiel et al., 2012; Renfree et al., 2014; Aragón et al., 2016; Casado and Renfree, 2018; Hanley et al., 2018), we show the race kick as a key tactical behavior, that interestingly occurred on the last lap irrespective of the race category (**Figure 2**). For the first time we highlight the important differences in the role of tactical position at initiation of the race kick between fast, medium and slow races. To win the gold medal in fast races, athletes at the race kick on average were shown to be in the top 2 positions, vs. top 4 in medium and slow races, respectively (**Figures 3A–C**). Importantly in slow pace races, there was no substantial difference in tactical position at the race kick of all eventual medalists (**Figure 3C**). Together these findings have numerous methodological implications for future research studies alongside training and tactical preparation for coaches and athletes toward championship racing.

An athlete has limited metabolic resources to portion across the course of a race (Fukuba and Whipp, 1999) and will self-regulate the use of this resource according to environmental feedback (weather conditions, opponents position, surging) to put themselves in an eventual medal-winning position. This demonstrates a concept known as affordance-weighted decision making (Hettinga et al., 2017). In a slow race, all athletes typically operate at a relatively low rating of perceived exertion in the early laps (∼critical velocity; Sandford et al., 2019), and therefore everyone is vulnerable to a surge attack. This leads to an increase in tension about tactically being in a "good position," which may in part explain the increase in the number of sometimes erratic of mid-race surges (**Figure 1**; Konings and Hettinga, 2018). Developing in-race positional awareness, subsequent tactical agility and affordance-weighted decision making becomes increasingly important the slower the race, with surges continuing to happen very close to the race kick in both medium and slow races (**Figure 2**). In contrast, a fast paced race has a higher perception of effort and given physiological strain from the start line (Tucker et al., 2006). Seemingly this reduces the tactical decision making element of having to be in position (i.e., fewer surges; **Figure 1**), as attention is focused on trying to stay with the fast pace, akin to that of a world record attempt (Tucker et al., 2006; Foster et al., 2014) (i.e., if an athlete cannot stay with a fast early pace, they will not be in the medal-winning positions, irrespective of tactics). In support of this explanation, **Figure 2** also shows that the final surge before the race kick happens on average substantially earlier in the fast races than in medium and slow pace races.

A notable aspect of this paper is the characterization of eventual medalist positioning at key tactical landmarks (e.g., the race kick; **Figures 3A–C**). Eventual gold and silver medalists were found to be positioned higher at the race kick in fast races than the bronze medalist (top 2 vs. top 4, respectively). In contrast, in slow races, unclear differences between eventual gold, silver and bronze medalists' position at the race kick, may reflect the fact that when the race is slow, everyone has increased probability of winning, as shown previously (Casado and Renfree, 2018). The present results build on the 2001–2012 analysis by Aragón et al. (2016) who found all race winners were in the top 4 when the finishing race kick was initiated, though these races were not categorized by pace category. Furthermore, Renfree et al. (2014) in a London 2012 Olympic case study, showed a correlation of ≥0.70 between a top 5 position with 300 m to go and finishing in a top 3 automatic qualifying position, representing a similar landmark to where the race kick occurred in **Figure 2**. Together these findings highlight the importance of enhancing in-race decision making (Hettinga et al., 2017) and preparation for multiple race scenarios (fast, medium, and slow) at championship events.

The present work offers several methodological advances in analysis of middle-distance tactical behavior. Understanding the nuance in tactical behavior between different race categories is limited within the scientific literature (Hanley et al., 2018), where race narratives often lie at the extremes (e.g., either one of "sit and kick," or "gun to tape"; Mytton et al., 2015; Casado and Renfree, 2018). Our data shows there are important changes in tactical behavior (surge and position) as races become slower, creating deeper tactical insight and generating more avenues for further investigation. Additionally, through using expert observation in middle-distance running, we were able to provide greater resolution (within 10 m) on distances from the finish that surge and race kick events occurred, building on the one previous paper that has used resolution beyond 100 m sectors (Aragón et al., 2016). By adopting this novel observational method of analysis, we were able to illustrate corresponding positional changes of medal winning athletes at each surge and race kick event. This method allows deeper insight into within-race tactical behavior than that previously available and warrants further investigation across a wider cohort of event classifications and between genders.

Despite these advances to the literature, there are several methodological challenges that require consideration. For example, there is an assumption in our present methodology that all surges are the same (acceleration rate, repositioning of places due to pace gain etc.), which is a clear limitation. Further, our observational methods used only three expert judgements. We tempered any single sided bias by having multiple experts, and a second level verification, which whilst not objective, was performed by experienced practitioners (1st and third author). Human physical potential is sigmoidal (Tucker and Collins, 2012) and therefore, by nature of the study emphasis (European, Olympic and World Champions), there are a limited number of (a) races and (b) experts experienced in classifying tactical behavior of elite 1,500 m running. Creation of new methods (both manual observations and technology aided athlete tracking) to characterize such nuance would be beneficial in future studies, and would enable detailed tactical profiling of championship races and athletes.

PRACTICAL APPLICATION

Within professional track and field racing, it can be a challenge for 1,500 m athletes to find quality races that are not set-up with a pace maker (e.g., Diamond league, European, and North American racing circuits) in order to prepare for major championship racing. This raises the question of how the tactical component in races with lots of surges and in-racing decision making i.e., slow or medium pace races (**Figure 1**) can be rehearsed ahead of championships. For example, perhaps tactical training session design or use of video analysis review to prepare athletes for a multitude of possible scenarios is an important consideration. Furthermore, developing athlete's affordance-based decision making to be resilient to uncontrollable opponent surges, could be a key competitive advantage. For example when the race starts out slow, athletes need to be prepared psychologically that there may be 1–2 surges every lap (**Figure 1**), and ultimately, the athlete needs to find confidence and flow to execute in a championship race. Top athletes must instinctively respond to, or dictate key tactical events. Nevertheless, current knowledge and rehearsal of tactical expectations in the practice arena, is perhaps an overlooked aspect of championship racing preparation.

CONCLUSION

In agreement with previous tactical papers we highlight the clear role of the race kick in determining eventual championship race medalists, where, regardless of race category, the race kick occurred on the last lap. Importantly for the first time, three race categories across a continuum highlight substantial differences in surge events and tactical positioning before, and at initiation of the race kick. These new tactical insights have important implications for the tactical preparation of athletes and coaches for championship race execution.

DATA AVAILABILITY STATEMENT

The datasets for this manuscript are not publicly available because the data arose as a function of an employed position and therefore the rights to the data are owned by the employer at the time (High Performance Sport New Zealand) as Intellectual property.

AUTHOR CONTRIBUTIONS

GS, BD, and SR contributed to conception and design of the study, manuscript, figure and table revision, read and approved the submitted version. BD organized the database and produced first draft of the figures. GS and SR verified expert observation results. GS performed the statistical analysis and wrote the first draft of the manuscript.

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Humans Optimize Ground Contact Time and Leg Stiffness to Minimize the Metabolic Cost of Running

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Trained endurance runners appear to fine-tune running mechanics to minimize metabolic cost. Referred to as self-optimization, the support for this concept has primarily been collated from only a few gait (e.g., stride frequency, length) and physiological (e.g., oxygen consumption, heart rate) characteristics. To extend our understanding, the aim of this study was to examine the effect of manipulating ground contact time on the metabolic cost of running in trained endurance runners. Additionally, the relationships between metabolic cost, and leg stiffness and perceived effort were examined. Ten participants completed 5 × 6-min treadmill running conditions. Self-selected ground contact time and step frequency were determined during habitual running, which was followed by ground contact times being increased or decreased in four subsequent conditions whilst maintaining step frequency (2.67 ± 0.15 Hz). The same self-selected running velocity was used across all conditions for each participant ($12.7 \pm 1.6\ \text{km} \cdot \text{h}^{-1}$). Oxygen consumption was used to compute the metabolic cost of running and ratings of perceived exertion (RPE) were recorded for each run. Ground contact time and step frequency were used to estimate leg stiffness. Identifiable minimums and a curvilinear relationship between ground contact time and metabolic cost was found for all runners ($r^2 = 0.84$). A similar relationship was observed between leg stiffness and metabolic cost ($r^2 = 0.83$). Most (90%) runners self-selected a ground contact time and leg stiffness that produced metabolic costs within 5% of their mathematical optimal. The majority ($n = 6$) of self-selected ground contact times were shorter than mathematical optimals, whilst the majority ($n = 7$) of self-selected leg stiffness' were higher than mathematical optimals. Metabolic cost and RPE were moderately associated ($r_s = 0.358$ $p = 0.011$), but controlling for condition (habitual/manipulated) weakened this relationship ($r_s = 0.302$, $p = 0.035$). Both ground contact time and leg stiffness appear to be self-optimized characteristics, as trained runners were operating at or close to their mathematical optimal. The majority of runners favored a self-selected gait that may rely on elastic energy storage and release due to shorter ground contact times and higher leg stiffness's than optimal. Using RPE as a surrogate measure of metabolic cost during manipulated running gait is not recommended.

Keywords: self-optimization, oxygen consumption, running mechanics, running economy, perceived effort

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INTRODUCTION

Self-optimization is the subconscious, fine-tuning of running mechanics to minimize metabolic cost (Cavanagh and Williams, 1982; Williams and Cavanagh, 1987; Moore et al., 2012, 2016), and is believed to be central to developing an economical running gait. Hogberg (1952) provided the first example of systematically manipulating stride length to examine self-optimization in a trained runner and reporting the resultant metabolic response. This initial work was applied to a larger cohort ($n = 10$) of trained runners by Cavanagh and Williams (1982). In both studies, a curvilinear, U-shaped relationship was observed highlighting that trained runners were able to self-select a stride length that was at, or near to, their mathematically derived optimal stride length. Others have replicated these findings (Morgan et al., 1994; Hunter and Smith, 2007; de Ruiter et al., 2013; Connick and Li, 2014; van Oeveren et al., 2017) and extended the knowledge base by demonstrating that untrained runners are further from their mathematical optimal than trained runners (de Ruiter et al., 2013) and submaximal running velocity does not affect the optimal stride length (van Oeveren et al., 2017). Additionally, even when fatigued, trained runners produce stride lengths that are near their mathematically derived optimal (Hunter and Smith, 2007). Consequently, it has become well recognized that stride length and frequency are self-optimized within trained runners. Yet, limited attention has been given to assessing the optimization of how stride frequency is produced, specifically, consideration of ground contact time, which may elicit different athlete-specific responses when manipulated.

Reported associations between ground contact time and metabolic cost have been equivocal (Moore, 2016). Early work proposed that ground contact time was inversely proportional to the energetic cost of walking and running (Kram and Taylor, 1990; Hoyt et al., 1994; Kipp et al., 2018), meaning increasing contact time would reduce the energy required to travel a unit distance. Such an association has been observed by Di Michele and Merni (2013) and Williams and Cavanagh (1986). However, the time spent in contact with the ground has since been identified as the metabolically expensive phase of the gait cycle (Arellano and Kram, 2014), leading many to advocate that shorter ground contact times would facilitate a reduction in metabolic cost (Nummela et al., 2007; Santos-Concejero et al., 2014; Folland et al., 2017). Whilst studies have supported associations to this effect (Nummela et al., 2007; Santos-Concejero et al., 2014, 2017), conclusive causative evidence has not been forthcoming. Recently, Lussiana et al. (2019) observed that short and long ground contact times may be economically beneficial depending on the type of runner you are. Runners who spend a relatively large proportion of the gait cycle in contact with the ground (high duty factor) had similar metabolic costs as those who spend a relatively small proportion of the gait cycle in contact with the ground (low duty factor) (Lussiana et al., 2019). These findings add further support to the theory of self-optimization, as runners appeared to have subconsciously adapted both mechanically and physiologically. Accordingly, the challenges presented by current research based on cross-comparisons examining contact time and metabolic cost, means that athlete-specific recommendations about economical running and this specific gait characteristic remain elusive (Moore, 2016).

Morin et al. (2007) have been the only researchers to use a within-participant design to study ground contact time. Specifically, they were able to manipulate ground contact time and demonstrated that changes in the time spent in contact with the ground explained a larger proportion of variance in changes in leg stiffness than changes in stride frequency ($r^2 =$ 0.90 and 0.47, respectively). Whilst the study did not measure the metabolic cost of running, greater leg stiffness has been found to be related to a lower metabolic cost (Dalleau et al., 1998) and is seen as an economical running strategy (Moore, 2016). Therefore, it could be argued that producing a greater leg stiffness whilst simultaneously maintaining stride frequency, facilitated by shorter ground contact times, would reduce the metabolic cost of running. Calculating leg stiffness is derived from the concept that human running can be explained by a spring-mass model (Blickhan, 1989). The *spring* represents the leg, which is compressed by the body during the first half of ground contact and then rebounds upwards during the second half of ground contact (Morin et al., 2005). A stiffer leg would potentially store and release energy more effectively than a less stiff leg and subsequently this may reduce the metabolic cost of running. Aside from the study by Morin et al. (2007), ground contact time and leg stiffness have received limited attention from within-participant study designs investigating economical running.

Assessing a runner's ground contact time can be performed with relatively simple equipment, such as a video camera or phone application (Balsalobre-Fernández et al., 2017), which has enabled biomechanical analysis to become more accessible to coaches and practitioners. However, determining optimal ground contact times with respect to metabolic cost currently requires expensive equipment to measure the constitution of inspired and expired air (e.g., gas analysis system), and technical expertise. Surrogate measures have been effectively adopted in assessing stride length and frequency (de Ruiter et al., 2013), but still require additional equipment. It is possible that Ratings of Perceived Exertion (RPE) could provide a surrogate, affordable, and easy to use measure to examine the perceived demand of manipulating ground contact time. Several studies have shown that the metabolic cost of running is linearly related to perceived exertion (see Chen et al., 2002 for a review) so it would seem plausible that it would be effective. Further, due to the relationship between RPE and metabolic cost, RPE is often used by coaches and practitioners to monitor training responses (McLaren et al., 2018), but it is not known whether this is an appropriate surrogate measure to use for technique-focused training.

The primary aim of this study was to examine the effect of manipulating ground contact time on the metabolic cost of running, in addition to determining the effect of altered leg stiffness on the metabolic cost of running. Based on the self-optimization theory, it was hypothesized that the trained runners would self-select a ground contact time and leg stiffness near to their mathematically derived metabolically optimal ground contact time (within 5%). The mathematical optimal being an identifiable minimum in a curvilinear relationship between metabolic cost and the gait characteristics. A secondary aim was to assess the relationship between metabolic cost and perceived exertion across the different ground contact time conditions and we hypothesized that a positive, linear relationship would be observed between metabolic cost and perceived exertion.

METHODS

Participants

Ten trained, university level endurance runners (nine male and one female) provided informed, written consent to participate in the study (age: 19.8 ± 2.6 years; height: 1.79 ± 0.12 m; mass: 65.1 ± 6.6 kg). Each participant completed a minimum of two structured training sessions per week, were part of the athletics first team squad and could run sub-17 min 5 km or sub-35 min (male) and sub-45 min 10 km (female). Additionally, all participants were familiar with treadmill running and had been injury-free for the previous 6 months. Ethical approval was obtained from the University's Ethics Committee.

Procedure

All running conditions were undertaken during one visit to the laboratory. Mass and height were measured prior to commencing the warm-up. All participants performed a self-selected warm-up for between 5 and 10 min during which time they were familiarized to the cues that were about to be provided. Participants were then instructed to self-select a running velocity that they believed they could comfortably maintain for 30 min. Participants then completed 5 × 6-min treadmill runs at their self-selected running velocity (12.7 ± 1.6 $\text{km} \cdot \text{h}^{-1}$), with 3 min rest periods between consecutive bouts. The self-selected running velocity was deemed to be submaximal based on data from the habitual condition producing a respiratory exchange ratio <1.0 during the final 2 min of the run. During the first run, participants performed their habitual running technique, which allowed their self-selected step frequency and ground contact time to be determined via the *Runmatic* app. Participants then performed four separate runs in a standardized order, whereby a specific verbal cue was provided to elicit one of the four conditions: slow contact time, very slow contact time, quick contact time and very quick contact time. During each condition, a metronome was used to maintain the participants' step frequency at a rate that matched their self-selected frequency. The specific verbal instructions provided were "make contact with the ground in time with the beat of the metronome and to respond to the cue provided." The verbal cue was given every 30s (Moore et al., 2019) and were as follows: condition (1) increase contact time more than usual; condition (2) increase contact time as much as possible; condition (3) decrease contact time more than usual and; condition (4) decrease contact time as much as possible. Throughout each run breath-by-breath respiratory data were recorded using an online gas analysis system (OxyconPro, Jaeger at Viasys Healthcare, Warwick, UK) and RPE was recorded on Borg's 6–20 scale (Borg, 1998) at the end of each run. All participants wore their usual training attire and ran in their own trainers.

Data Collection and Computation

Participants were video recorded in the frontal plane using the *Runmatic* app (250 Hz) on an iPhone to enable ground contact time for the left and right feet to be determined. The set-up followed previous recommendations whereby the iPhone is held 30 cm from the back of the treadmill, vertically in line with the height of the treadmill (Balsalobre-Fernández et al., 2017). The *Runmatic* app has been shown to provide a valid measure of ground contact time (ICC >0.96 with criterion measurement) and strong intra-session reliability when using 10 foot contacts ($\alpha = 0.996$) (Balsalobre-Fernández et al., 2017). A 10 s recording was taken during the 4th min of each condition, which led to five gait cycles (10 foot contacts). The videos were manually digitized within *Runmatic* app by the same individual and ground contact time, aerial time, and step frequency data were exported for each condition. Ground contact time (s) was defined as the time between initial foot contact and toe-off for the same foot, whilst aerial time (s) was the time between toe-off from one foot to initial contact of the other foot. Finally, step frequency (Hz) represents the number of foot contacts (left and right) during one unit of time (s). Following the recommendations of Morin et al. (2005), leg stiffness ($\text{N} \cdot \text{m}^{-1}$) was calculated using the exported ground contact and aerial times, the estimated peak vertical force (N) from the sine wave method and the modeled vertical displacement of the center of mass (m) during ground contact. Full details can be found in **Supplementary 1**. The unit change for the relationship between ground contact time and leg stiffness was calculated using the gradient of the slope created by the interpolated ground contact time and interpolated leg stiffness. The interpolation procedure is described below.

Oxygen consumption data were filtered using a recursive low-pass, second order Butterworth filter (0.43 Hz cut-off frequency determined using residual analysis) and the mean metabolic cost was computed using the final 2 min of each run. Datasets were checked for outliers (2 SD away from the mean) and any within-participant outliers for each run were removed prior to the mean metabolic cost being calculated. All oxygen consumption data were visually checked for the presence of a steady-state. Metabolic cost was computed using the oxygen consumed per unit body mass per unit time ($\text{ml O}_2 \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$). Using metabolic cost per unit distance ($\text{ml O}_2 \cdot \text{kg}^{-1} \cdot \text{km}^{-1}$) rather than per unit time did not alter the relationships identified in the study.

Optimal ground contact time was determined separately for each participant using the metabolic cost. Specifically, a least-squares cubic interpolation (third order polynomial, interpolated to fifty data points) with ground contact time as the independent variable and metabolic cost as the dependent variable was calculated. Cubic interpolation was employed to accommodate the potential asymmetrical increase in metabolic cost either side of the optimum and any asymmetrical increases and decreases in ground contact, as the magnitudes of ground contact time changes could not be controlled. The cubic interpolation was constrained by the habitual ground contact

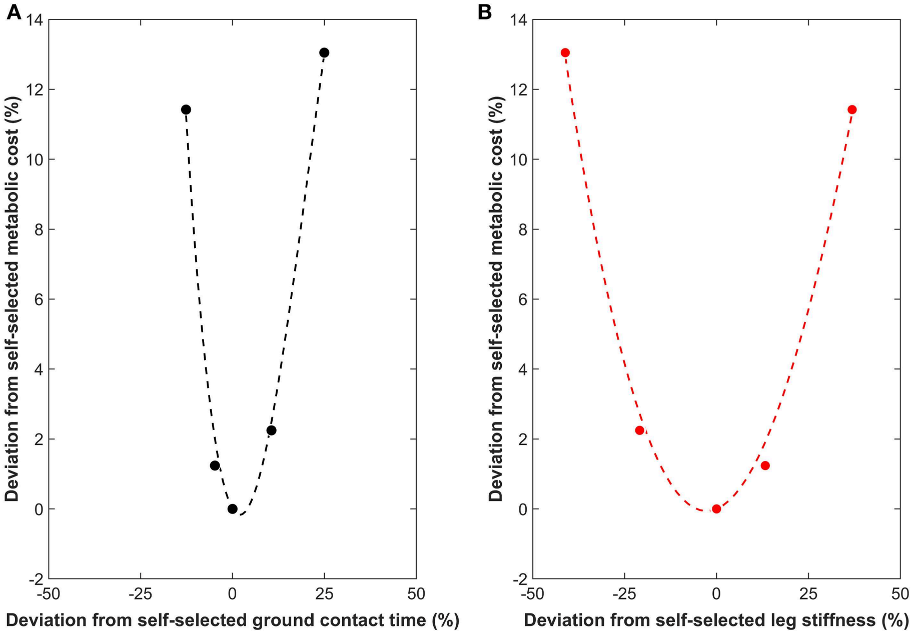

FIGURE 1 | Example measured (filled circles) and interpolated (dotted line) data showing the relationship between the deviations from the self-selected running gait characteristics (%) and from the metabolic cost during self-selected gait (%). **(A)** Ground contact time (• and black dotted line). **(B)** Leg stiffness (● and red dotted line). Both relationships are shown to the same scale on the x and y-axes to highlight the differences in the slope steepness at the base of the curve (surrounding minimum).

time and oxygen consumption being a known, fixed point on the third order polynomial. The minimum of the cubic interpolation was identified using the *fmincon* function in MATLAB (Mathworks, Inc., 2018b) between the following bounds: fastest ground contact time (lower bound) and slowest ground contact time (upper bound). The procedure was repeated for leg stiffness as the independent variable and metabolic cost the dependent variable. **Figure 1** shows an example of measured and interpolated data. All computations were performed in MATLAB. A free downloadable software has been developed to allow others to compute optimal gait characteristics (Moore, 2019).

Statistical Analysis

Means (SDs) of the biomechanical variables derived from both the left and right steps were computed for each individual during each condition. After normality testing using Sharipo-Wilk ($W = 0.980$, $p = 0.551$), a one-way repeated measures ANOVA was used to check whether step frequency was maintained across all running conditions. Due to RPE data being ordinal, a Spearman's rank test was used to assess the association between RPE and metabolic cost and a partial Spearman's rank test was used to assess the same association but with the type of running condition (habitual and manipulated) controlled for. Small, medium and large strengths of association were defined as 0.10–0.29, 0.30–0.49, and $\geq$0.5, respectively. Statistical analyses were conducted with RStudio (version 1.1.456, Boston, MA) and alpha was set at 0.05.

RESULTS

Step frequency [$F_{(1,40)} = 0.051$, $p = 0.995$] was found to be similar across all conditions (mean ± SD: 2.67 ± 0.15 Hz). This confirms that the habitual step frequency was maintained throughout. The mean self-selected ground contact time was 0.247 ± 0.016 s, with a mean metabolic cost of 45.34 ± 5.42 $\mathrm{ml\ O_2 \cdot kg^{-1} \cdot min^{-1}}$. A mathematical optimal ground contact time was identifiable for all participants using a third order polynomial, with a large proportion of variance in metabolic cost explained by ground contact time ($r^2 = 0.840$; **Table 1**). On an individual level, six participants used a self-selected ground contact time that was 1–8% shorter than their mathematical optimal, whilst the remaining four participants used a self-selected ground contact time that was 1–5% longer than their mathematical optimal (**Table 1**; **Figure 1**).

The mean self-selected leg stiffness was 8.38 ± 1.33 $\mathrm{kN \cdot m^{-1}}$, with a mathematical optimal leg stiffness identifiable for all participants. A similar amount of variance in metabolic cost could be explained by leg stiffness ($r^2 = 0.826$), as it was with ground contact time. The majority ($n = 7$) of the participants used a self-selected leg stiffness that was 1–16% higher than their mathematical optimal compared to three participants who used a self-selected leg stiffness that was 1–6% lower than their mathematical optimal (**Table 1**).

Half of the participants ($n = 5$) were within 1% of their optimal metabolic cost, and all participants bar one were within 5% of their optimal metabolic cost (**Figure 2**). Example relationships between metabolic cost and ground contact time are presented in **Figure 3** for the three different responses produced

TABLE 1 | Self-selected and mathematical optimal (% of self-selected) ground contact times and metabolic costs for each participant, with the third order polynomial modeled fit (r^2).

Participant number	Self-selected			Mathematical optimal (% of self-selected)				Modeled fit (R^2)	
	Ground contact time (s)	Leg stiffness ($N \cdot m^{-1}$)	Metabolic cost (ml $O_2 \cdot kg^{-1} \cdot min^{-1}$)	Ground contact time	Metabolic cost	Leg stiffness	Metabolic cost	Ground contact time	Leg stiffness
1	0.280	7,915	44.50	3.12	2.25	−5.61	1.85	0.859	0.964
2	0.251	7,892	47.87	−0.42	0.05	1.13	0.07	0.941	0.944
3	0.230	9,892	46.11	4.46	0.46	−6.26	0.21	0.916	0.913
4	0.234	7,995	48.93	1.23	0.47	−1.81	0.21	0.957	0.970
5	0.261	7,508	40.79	1.97	0.17	−2.73	0.06	0.996	0.995
6	0.239	7,150	51.06	−2.06	3.51	5.74	5.01	0.606	0.331
7	0.236	10,766	46.89	7.81	3.91	−15.64	4.20	0.850	0.856
8	0.245	6,892	49.55	8.18	10.55	−14.73	11.02	0.847	0.995
9	0.258	7,859	45.39	−4.50	1.20	−1.35	0.03	0.739	0.719
10	0.232	9958	32.26	−3.42	0.72	0.31	0.01	0.690	0.576
Mean (SD)	**0.247 (0.016)**	**8,383 (1,326)**	**45.34 (5.42)**	**1.64 (4.38)**	**2.33 (3.20)**	**−4.10 (6.76)**	**2.27 (3.60)**	**0.840 (0.125)**	**0.826 (0.221)**

Nb. A positive percentage of self-selected indicates the optimal gait characteristic was higher than the habitual gait (longer ground contact time or higher leg stiffness). A negative percentage of self-selected indicates the optimal gait characteristic was lower than the habitual gait (shorter ground contact time or lower leg stiffness).

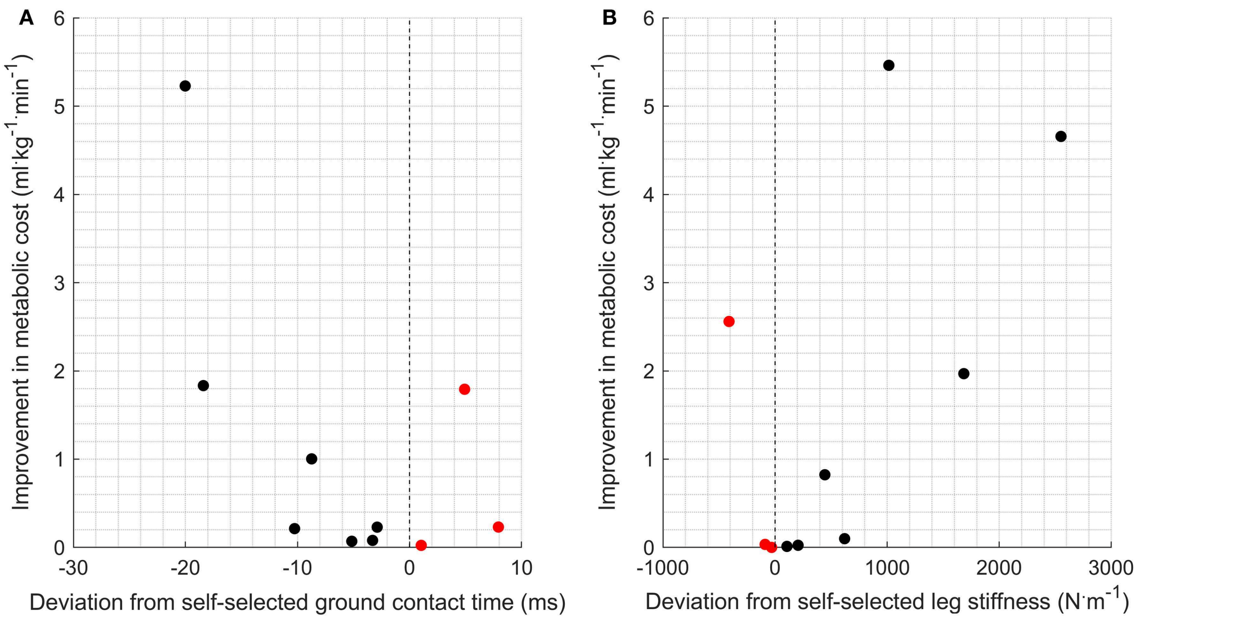

FIGURE 2 | Mathematically optimal ground contact time [ms; **(A)**] and leg stiffness [$N.m^{-1}$; **(B)**] as a deviation from self-selected gait characteristics and their corresponding improvement in metabolic cost ($ml.kg^{-1} \cdot min^{-1}$). Improvement represents a reduction in metabolic cost compared to the metabolic cost associated with a self-selected gait. Black dots (•) represent runners with shorter self-selected ground contact times than optimal and higher leg stiffness. Red dots (●) represent runners with longer self-selected contact times than optimal and lower leg stiffness.

by participants: ground contact times shorter than, near to, and longer than their mathematical optimal. The corresponding metabolic cost and leg stiffness relationships are also shown. The within-participant mean unit change in ground contact time relative to the mean unit change in leg stiffness was 1:2.2 ± 0.2, meaning for every 1% change in ground contact time a 2.2% change in leg stiffness was observed (**Figure 4**).

There was a medium strength, significant association between RPE and metabolic cost ($r_s = 0.358$, $p = 0.011$). When the habitual running condition was controlled for using a partial

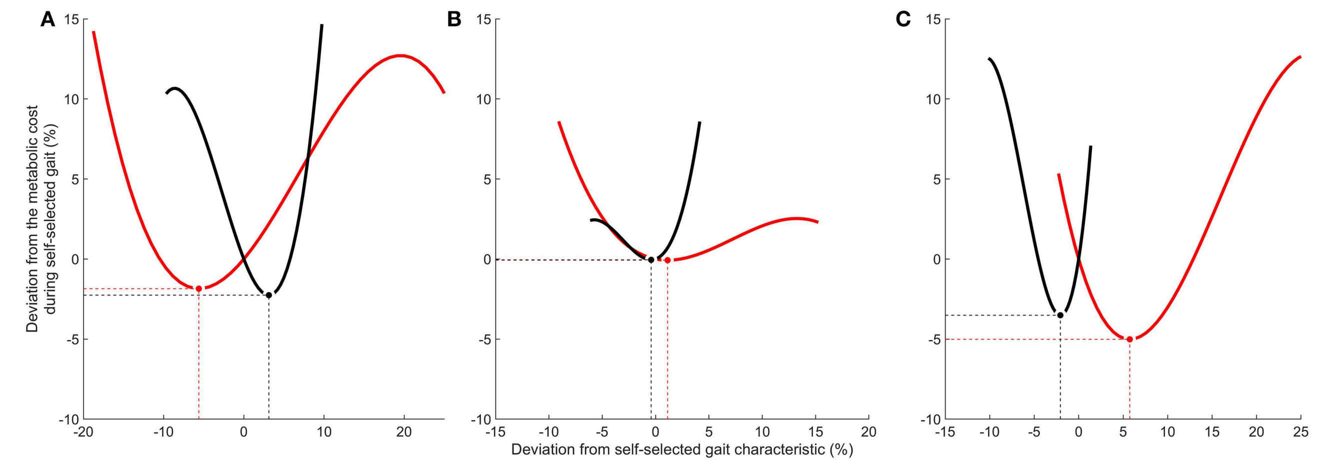

FIGURE 3 | Relationship between the deviations from the self-selected running gait characteristics (%) and from the metabolic cost during self-selected gait (%). **(A)** Example of self-selected ground contact time longer than optimal. **(B)** Example of self-selected ground contact time within 1% of optimal. **(C)** Example of self-selected ground contact time shorter than optimal. Solid black lines represent ground contact time. Solid red lines represent leg stiffness. Optimal gait characteristics that minimize metabolic cost are identified by circles [black (•) = ground contact time; red (●) = leg stiffness]. Dashed lines highlight the corresponding X and Y values for optimal gait characteristics.

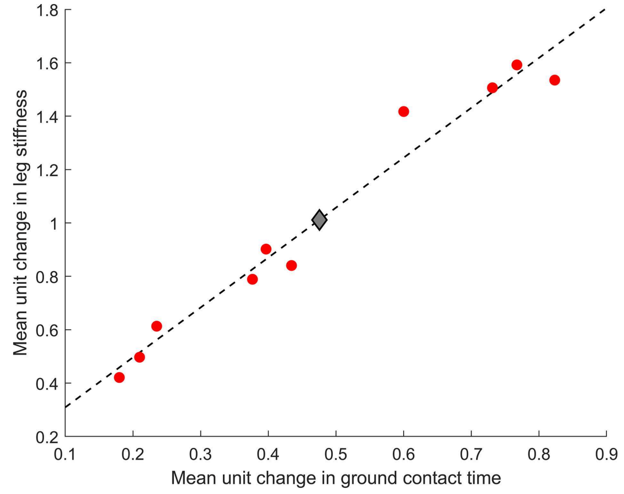

FIGURE 4 | Mean unit change in ground contact time and leg stiffness for the group (◆) and each participant (●). Dashed line represents the line of best fit [leg stiffness = 1.9(ground contact time) + 0.12].

correlation, the strength of the association weakened ($r_s = 0.302$, $p = 0.035$).

DISCUSSION

The aim of this study was to examine the effect of manipulating ground contact time on the metabolic cost of running, in addition to determining the effect of altered leg stiffness on the metabolic cost of running. It was the first study to identify that ground contact time and leg stiffness are self-optimized gait characteristics, as it was observed that trained runners are operating at, or close to, their mathematical economical optimal during submaximal running. In addition, nearly all runners (90%) were using self-selected ground contact times and leg stiffness's that produced metabolic costs within 5% of their mathematical optimal metabolic cost. These findings build upon early work by Hogberg (1952) and Cavanagh and Williams (1982), suggesting that physiological and mechanical adaptations produced during repeated exposure to stimuli allows runners to fine-tune their gait to minimize the metabolic cost of running. With regard to metabolic cost and RPE, while there was a relationship between the variables, it was weakened when the habitual running condition was controlled for. This suggests RPE may not be a useful surrogate measure for metabolic cost when manipulating gait.

In support of our first hypothesis an identifiable optimal (minimum) was observed for all runners, and a curvilinear, U-shaped relationship appeared to be present between metabolic cost, and ground contact time and leg stiffness (example data **Figure 2**). These findings support the theory of self-optimization, but contradict previous research that argued shorter (Nummela et al., 2007; Santos-Concejero et al., 2014, 2017; Folland et al., 2017) or longer (Williams and Cavanagh, 1986; Kram and Taylor, 1990; Di Michele and Merni, 2013) ground contact times are an economical running characteristic and greater leg stiffness reduces metabolic cost (Dalleau et al., 1998). However, these previous studies used cross-comparisons to determine differences in gait between runners. Such an approach provides a rich database of gait characteristics that might function to reduce metabolic cost, yet individually profiling how runners respond to gait manipulations appears more informative for understanding economical running. Therefore, extrapolating ground contact times from one runner to another to assess economical running should be undertaken with caution.

Ground contact time appears to have a narrow optimal range that runners can operate within, inducing changes to metabolic cost with only minor alterations to ground contact time, as shown by a relatively steeper portion at the base of the curve (surrounding minimum) than leg stiffness (**Figures 1**, **3**). In contrast, leg stiffness has flatter portions at the base of the curves, a trait that is also shared with stride length and stride frequency (Cavanagh and Williams, 1982). Such a trait may accommodate a runner's natural variation in gait or reflect adaptations to different training stimuli e.g., terrain, velocity. For example, leg stiffness functions to maintain a stable running gait in humans and animals (Seyfarth et al., 2002), and can be rapidly adjusted when running over different surfaces (Ferris et al., 1998) and obstacles (Birn-Jeffery et al., 2014) to preserve center of mass displacement. Therefore, the ability to alter leg stiffness within a broader optimal range than ground contact time without increasing metabolic cost may be a beneficial economical strategy. However, it also suggests that optimal ground contact time is of greater importance than leg stiffness or stride frequency/length for economically optimal movement criteria.

During stable running with varying stride frequencies, leg stiffness adjustments also lead to the generation of a constant leg force (Farley and González, 1996; Seyfarth et al., 2002). We conducted subsequent correlation analysis to test if constant leg force was present and found it not to be the case when leg stiffness is rapidly adjusted to accommodate shorter and longer ground contact times. Specifically, leg stiffness was positively associated with leg force (estimated peak vertical force; $r_s = 0.639$, $p < 0.001$), whereas if leg force was constant no relationship would be present. The running velocity and step frequency constraints placed upon runners in the current study would have restricted the degrees of freedom each runner had to adjust their leg stiffness, potentially leading to this apparent homogenous response of altered leg force. It is conceivable this reflects an optimized adaptation, developed through exposure to running and training stimuli allowing trained runners to rapidly accommodate leg stiffness adjustments. Arguably, similar homogenous responses may not be found in untrained runners, as they have shown less consistent responses to increases in running velocity and are further away from their mathematical optimal than trained runners (de Ruiter et al., 2013; Bitchell et al., 2019), however, further work in this area is warranted.

The majority ($n = 6$) of runners used self-selected ground contact times and leg stiffness's that were shorter and higher, respectively, than their mathematical optimal. This means they are favoring the production of rapid and high magnitudes of vertical force, generated by a stiff lower limb. Combining this understanding with previous work that identified that the majority of trained runners favored overstriding (longer stride times than optimal) (Cavanagh and Williams, 1982; de Ruiter et al., 2013), suggests trained runners favor a low duty factor indicating they rely on the storage and release of elastic energy to minimize metabolic cost (Lussiana et al., 2019). To achieve this, muscles would also be required to operate at faster shortening velocities, requiring more motor units to be recruited to produce the necessary high forces (Fletcher and MacIntosh, 2017). Factors such as training stimuli and intrinsic muscle-tendon properties may mean a runner's musculoskeletal system is tuned to such demands. However, such a mechanical strategy would induce high vertical and horizontal loading rates and magnitudes of impact-related forces, which may place the runner at risk of lower limb injury (Hreljac et al., 2000; Napier et al., 2018). A few ($n = 4$) runners adopted a different mechanical strategy, whereby they had longer ground contact times and a more compliant leg (less stiff) than their mathematical optimal. This would induce a higher duty factor than optimal, indicating the runners were prioritizing horizontal displacement and reducing vertical displacement (Lussiana et al., 2019). In contrast to the low duty factor strategy, muscles would operate at slower shortening velocities, needing fewer motor units to be recruited to produce lower force (Fletcher and MacIntosh, 2017). This strategy may be indicative of poor intrinsic muscle-tendon stiffness or of prioritizing reducing work against gravity and impact-related forces.

As gait selection and self-optimization are deemed a subconscious processes (Cavanagh and Williams, 1982; Moore et al., 2012), it is conceivable that the majority of runners are unknowingly prioritizing minimizing metabolic cost rather than minimizing potentially detrimental impact-related forces. This could be because the detection of impact-related forces by the musculoskeletal and neural systems may not be as sensitive as the detection of metabolic demand by the cardiovascular system. Even with footwear removed and therefore heightened somatosensory feedback, foot plantar surface sensitivity shows no relationship with foot peak pressures during the braking phase (Nurse and Nigg, 1999). With somatosensory feedback potentially being dampened further with cushioning found in traditional running footwear, it is unsurprising that humans appear more tuned to metabolic demands rather than impact forces.

By instructing runners to shorten or lengthen their ground contact time we were able to uniquely test the effect of ground contact time on metabolic cost, whilst constraining running velocity, step frequency/length, and thus, stride frequency/length. These constraints were important as they have known effects on metabolic cost (Gutmann et al., 2006). Interestingly, running velocity and stride frequency/length have received more attention than ground contact time, which has been largely ignored during constrained optimization testing when gait characteristics are manipulated (Knuttgen, 1961; Cavanagh and Williams, 1982; Gutmann et al., 2006; Hunter and Smith, 2007; de Ruiter et al., 2013). Given the significant role ground contact time appears to play in determining metabolic cost within humans and across bi-pedal and quadrupedal species during walking and running (Taylor et al., 1980, 1982; Kram and Taylor, 1990; Roberts et al., 1998), this oversight may have led to the simplification of locomotion optimization. Further, Fletcher and MacIntosh (2017) argued that runners maintain ground contact time rather than maximizing elastic energy storage and return due to selecting a lower stride frequency than optimal. Yet, by placing demands on the musculoskeletal system to rapidly adjust ground contact time in a constrained environment, we were able to identify that the majority of runners appeared to prioritize elastic energy storage and release, strengthening the need to consider ground contact time within the locomotion optimization equation.

To-date only one study has altered gait characteristics toward an individual's mathematical optimal. A 3-week intervention successfully altered stride frequency toward an individual's mathematical optimal and reduced metabolic cost in three runners (Morgan et al., 1994), showing the utility of gait retraining in expediting the self-optimization process. Although larger studies are required to confirm these findings, injury focused biomechanical retraining interventions with larger cohorts have shown desired running gait alterations can be achieved over a similar time period (Crowell and Davis, 2011; Roper et al., 2016). Strength based interventions may also be effective, but are likely to take longer to allow for physiological adaptations. For example, 3–4% longer ground contact times have been observed following an 8- (Ferrauti et al., 2010) and a 12- (Giovanelli et al., 2017) week strength intervention. Interestingly plyometric training, which is often advocated for runners as it focuses on improving the stretch-shortening cycle and stiffness characteristics of an individual, has no evidence to show the short ground contact times that are encouraged during training are transferred to running gait (Giovanelli et al., 2017; Gomez-Molina et al., 2018). Our study shows that trained runners are capable of altering leg stiffness following biomechanically-derived instructions and the mean unit change ratio (1:2.2) confirms previous reports that a 5% change in ground contact time corresponds to approximately a 10% change in leg stiffness (Morin et al., 2005, 2007). Therefore, biomechanical retraining is recommended as the first intervention approach if stiffness alterations are targeted due to the shorter time requirements and potential to re-assess ground contact time continuously during each training session.

The medium strength relationship between perceived effort and metabolic cost in the current study supports our second hypothesis, but is below the criterion presented by Chen et al. (2002) in their meta-analysis for treadmill exercise (95% CI for $r = 0.478–0.629$) and submaximal exercise (95% CI for $r = 0.766–0.870$). When the habitual running condition was controlled for the relationship weakened, suggesting the disrupted gait produced a disconnect between metabolic cost and perceived effort as previously observed in our laboratory (Moore et al., 2019). The act of manipulating running gait through verbal cues likely shifted attentional focus and heightened the sensed effort of the mechanical demand of running. Consequently based on the study's findings, in addition to recent work (Moore et al., 2019), utilizing perceived effort as a surrogate to determine the effect of changing running gait on metabolic cost and/or using it to monitor technique-focused training responses due to its association with metabolic cost should be undertaken with caution.

We acknowledge that there were several limitations in this study. Even though every participant received the same cues, individual interpretations resulted in self-selected changes in ground contact time. This led to some runners producing larger increases and decreases in ground contact time than others. Whilst, we were unable to overcome this within our laboratory, we believe cueing in this manner represents a useable gait retraining strategy for coaches and practitioners. Further, due to the between-participant variation in manipulated ground contact time the analysis focused on individual responses rather than group relationships. This approach, however, allows the identification of a range of responses, which coaches and practitioners may also observe and can quantify using the free software developed (Moore, 2019). Leg stiffness was estimated, rather than measured using gold standard techniques. However, the computations that were utilized have been validated for both overground and treadmill running, showing a low level of error bias (6%) for the latter (Morin et al., 2005). Additionally, the similar weighting of ground contact time on leg stiffness identified in this study compared to previous experimental and theoretical data support the assumption that it can represent human running behavior.

CONCLUSION

Ground contact time and leg stiffness were shown to be self-optimized in a group of trained runners, with all runners except one being within 5% of their optimal metabolic cost during their habitual running gait. Furthermore, identifiable minima were found for all runners suggesting the presence of curvilinear, U-shaped relationship between metabolic cost, and ground contact time and leg stiffness. Runners operated within a narrower band of optimal ground contact time than leg stiffness when running velocity and step frequency were constrained. Consequently, optimal ground contact time may have greater importance for economically optimal movement criteria than leg stiffness. The majority of runners favored a slightly shorter ground contact time and higher leg stiffness than optimal, suggesting a reliance on elastic energy storage and release and that the human body may be tuned to minimize metabolic cost rather than impact-related forces. Manipulating running gait appeared to disrupt the relationship between metabolic cost and perceived effort and, therefore, coaches and practitioners are not advised to use RPE as a surrogate measure during economical running gait assessments.

DATA AVAILABILITY STATEMENT

The datasets generated for this study can be found in the Figshare https://doi.org/10.25401/cardiffmet.8323307.v2.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Cardiff School of Sport and Health Sciences, Cardiff Metropolitan University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

ISM and KJA conceived and designed the study and drafted the manuscript. CC and JH recruited participants and undertook data collection. MM-R assisted with study design and data collection. ISM conducted the computational and statistical analysis. HSRJ contributed to the preparation of the manuscript. All authors provided critical insight in the final version.

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SUPPLEMENTARY MATERIAL

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The Impact of Sex and Performance Level on Pacing Behavior in a 24-h Ultramarathon

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Purpose: We analyzed the impact of sex, performance level and substantial speed reductions (SSR) on pacing in the VI Rio 24-h Marines Ultramarathon. This will provide insights into the importance of minimizing speed variations in relation to optimal pacing in endurance events.

Methods: Runners (30 males and 21 females), classified as high- (HP) and low-performance (LP) ran the race while having their time recorded every 400 m. The pacing was analyzed as the first 10% (initial epoch), the following 80% (intermediate epoch) and the last 10% of the race (final epoch). The time percentage spent at speeds $<$3.5 km·h^{-1} (SSR), 3.5 to 5.9 km·h^{-1} (walking speed), 6.0 to 8.0 km·h^{-1} (walk-to-running transition speed) and $>$ 8.0 km·h^{-1} (running speed) was calculated.

Results: Runners showed a reverse J-shaped pacing ($P < 0.001$) regardless of sex and performance level, although male ($P < 0.004$) and HP runners ($P < 0.001$) have preserved a higher mean speed throughout the race. Male and HP runners spent more time at running speed ($P < 0.001$) and less time at SSR ($P < 0.001$) than female and LP runners. Total distance was inversely correlated with the number of SSR and speed CV in male ($r = -0.47$ and $r = -0.64$, respectively) and female ($r = -0.61$ and $r = -0.47$, respectively).

Conclusion: Male, HP runners showed less SSR, conserving a higher mean speed with less variation throughout the race. Results suggest that conservative pacing strategies, with lower speeds in the beginning and higher speeds toward the end, may be the most adequate for different endurance running disciplines. Results also show different competition dynamics between men and women, which warrants further exploration in ultramarathons as well as other IAAF events.

Keywords: marathon, long distance running, performance, ultra-endurance, competition

INTRODUCTION

In endurance competitions with a known endpoint (i.e., distance or time), athletes have to constantly regulate their pace in order to finish the race in the shortest possible time or cover the largest possible distance (Abbiss and Laursen, 2008). This process is known as pacing, a key factor in optimizing endurance performance that involves the capacity to deal with physiological and perceptual responses as well as with environmental setting and race characteristics (Baden et al., 2005; St Clair Gibson et al., 2006; Esteve-Lanao et al., 2008; Tucker, 2009; Lima-Silva et al., 2010; Baron et al., 2011; Bath et al., 2012; Smits et al., 2014; Hettinga et al., 2017; Konings and Hettinga, 2018). In this regard, an inappropriate pacing strategy may result in a suboptimal performance, as athletes may have to deal with premature fatigue if, for instance, they choose an aggressive pacing strategy beyond their psychophysiological capabilities (Noakes et al., 2004, 2005; St Clair Gibson and Noakes, 2004). It is worth mentioning that, different from exercises performed at a controlled-pace such as time to exhaustion tests, self-paced exercises allow participants to pace themselves in response to physiological and perceived exertion perturbation so that a sustained pacing is maintained throughout the exercise (Tucker, 2009). This is particularly important in ultramarathons, as runners may frequently face different ground levels (i.e., sea level vs. mountains) and wind conditions in this very long running race. For example, ultramarathons held on mountains may challenge the successful pacing strategies due to climb and down phases, irregular terrains and light-to-strong winds.

In terms of endurance performances, different studies have investigated pacing strategies in running races with distances from 10 to 42 km, thus accounting for a duration ranging from ∼30 min to ∼2.5 h (Ely et al., 2008; March et al., 2011; Renfree and St Clair Gibson, 2013). However, running races with longer distances and durations such as ultramarathons, that have become increasingly popular in recent years, have been less investigated. This high-demanding race probably challenges the athletes' capacity to pace themselves, given the higher variation in weather conditions (Marino, 2004; Tucker, 2009), emotional responses (Baron et al., 2011), nutritional status (Jeukendrup, 2011), light and time of day (Fernandes et al., 2014; Pinheiro et al., 2016) as well as the occurrence of pain and fatigue (Millet et al., 2012). In this sense, the understanding of ultramarathon pacing and performance may be insightful to also understand other disciplines belonging to the International Association of Athletics Federations (IAAF) such as mountain running, given the challenging circumstances that athletes may face during these races. Although a few studies examining ultramarathon pacing strategies have observed a general positive pacing strategies in most parts of the event, with an increased speed in the last 10% (Lambert et al., 2004; Hoffman, 2014; Kerherve et al., 2015, 2016; Renfree et al., 2016), more studies are welcome to describe the likely beneficial pacing strategy of this race.

New insights regarding ultramarathon pacing behavior may be obtained from the analysis of the VI Rio 24-h Marines Ultramarathon dataset. For example, Bossi et al. (2017) analyzed data from 398 male and 103 female participants over five editions of this event, showing that athletes frequently use a reverse J-shaped pacing strategy in this 24-h running race. Using grouped data, the authors found that athletes used a fast start pace and then reduced the speed during the intermediate part of the race, before spurting during the final few hours. Interestingly, when using a dataset distinguished by sex, age or performance level, the authors found that neither sex nor age and performance level was related to the athletes' pacing strategy in different editions of the 24-h running race, thus indicating that a reversed J-shape pacing strategy was adopted by those athletes regardless of sex and performance level. These results contrasted previous ones in similar events (March et al., 2011; Renfree et al., 2016) which supported differences in pacing strategies between male and female runners with different performance levels. For example, while female runners are expected to be better pacers (March et al., 2011; Renfree and St Clair Gibson, 2013) likely due to differences in body size, fat metabolism and muscle fatigability (Hunter, 2016), higher performance runners usually adopt a more even pace than their slower partners (Renfree et al., 2016).

Nevertheless, more studies are required to explore the nuances of this very long race. For example, due to the prolonged duration athletes usually adopt breaks and walking periods in ultramarathons, as the completion of this race only by running seems impractical. Therefore, the use of high-frequency speed data rather than broad section averages may be needed to reveal how athletes incorporate breaks and walking periods in their pacing strategy. In fact, previous ultramarathon studies (Takayama et al., 2016; Bossi et al., 2017) have analyzed the 24-h running pacing strategy through 1 h mean data, thus likely disregarding speed variations in intervals lower than 1 h. In this perspective, it could be argued that 1 h time intervals are not long enough to accommodate important speed variations that may reflect either running or walking speeds. Moreover, another critical factor is the presence of breaks or substantial speed reductions (SSR) in ultramarathons, since it has been shown that a lower time spent with active/passive recovery periods was related to the best ultramarathon performance (Kerherve et al., 2015). Consequently, one hypothesis is that athletes planning their best 24-h ultramarathon performance may be oriented to avoid SSR. However, to the best of our knowledge no studies have attempted to describe the presence of SSR in 24-h ultramarathon races. Then, higher-frequency split data may be important to adequately describe the pacing strategy variations in this race (Angus and Waterhouse, 2011), so that analysis distinguished by sex and performance level may be more sensitive when considering the speed variations in time intervals over segments shorter than 1 h, which also allows for assessment of the presence of SSRs.

Therefore, in order to contribute to a better pacing guidance for very-long and high-demanding competitions such as a 24-h ultramarathon race, we aimed to analyze the impact of sex and performance level on the VI Rio 24-h Marines Ultramarathon pacing strategies using a higher-frequency split field data, thereby allowing us to include the number of SSR and verifying the association between SSR and 24-h ultramarathon performance. Importantly, this approach may be useful to improve the understanding of different endurance running disciplines as different studies analyzing running data from the IAAF have shown similarities in pacing profile of best male and female runners. Ultramarathon is an extreme endurance event, where any deviations from average speed are particularly pronounced, and is, therefore, a good model to explore the impact of speed variations over the race in endurance events in relation to optimal pacing.

MATERIALS AND METHODS

Participants

This study analyzed 51 ultramarathon runners (30 males and 21 females) selected from a dataset with 140 runners of the 2013 VI Rio 24-h Marines Ultramarathon ("*VI Ultramaratona Rio 24 h Fuzileiros Navais*"). The runners selected for this study completed at least 50% of the total distance completed by the winner (214.0 km for males and 193.2 km for females). This cutoff (i.e., 50% of the distance completed by the winner) was arbitrarily defined after visual inspection of the dataset, in order to provide a sample size distinguishable by sex and performance level, but without creating inconclusive pacing strategy profiles. The selected runners were between 31 and 35 (14%), 36–40 (20%), 41–45 (14%), 46–50 (10%), 51–55 (16%), 56–60 (12%), 61–65 (4%) and 66–70 (12%) years old. The distance completed in 24 h was 166.0 ± 18.9 km and 131.5 ± 26.5 km for male and female runners, respectively. The study was approved by the Ethics Committee of the Hospital Naval Marcílio Dias (protocol 1.059.358), and waived the requirement for written informed consent for participants in this study due to raw data were already freely available in the public domain and there were no interventions, in accordance with the national legislation and the institutional requirements.

24-h Ultramarathon Competition

The 24-h ultramarathon was performed on a 400 m running track at the Physical Education Center Admiral Adalberto Nunes, with the running direction around the track being changed every 2 h. The winners of female and male categories were those who completed the longest distance within the 24 h. Time elapsed was recorded every lap by an electronic timing system attached to the runners' footwear. The race started in a sunny day at 09:00 a.m. on 5th October 2013, finishing at 09:00 a.m. on the following morning, maintaining a good environmental condition during all the race. Minimum and maximal temperature, as well as relative air humidity, were recorded on 5th October, between 06:00 and 12:00 a.m. (23°C, 25°C, and 77%, respectively), 12:00–18:00 p.m. (23°C, 25°C, and 57%, respectively), 18:00–00:00 p.m. (21°C, 23°C, and 64%, respectively), and on 6th October between 00:00 and 06:00 a.m. (20°C, 20°C, and 69%, respectively) and between 06:00 and 12:00 a.m. (20°C, 26°C, and 64%, respectively). The runners were allowed to consume a variety of food and beverages *ad libitum*. Time and distance records were accessed on a free website hosting the race data (http://www.chiptiempo.com/resultados/inscriptor/vi-ultramaratona-rio-24h-fuzileiros-navais-66).

Data Analysis

We used the total distance covered within the 24 h as a performance indicator. In addition, pacing strategy analysis during this open-loop race was based on the distance completed within the 24 h. Thus, in accordance with previous works investigating the influence of the performance level on running pacing strategy (Lima-Silva et al., 2010; Bossi et al., 2017), we ranked runners according to tercile so that those runners within the lowest and highest tercile were designed as low (LP) and high performance (HP) groups, respectively. We discarded those runners within the intermediate tercile, as this ensured a comparison of pacing strategy profiles between distinguished different performance level groups. For pacing strategy analysis, we used the individual time elapsed recorded every 400 m to calculate the individual running speed within each 10 min interval, being expressed as absolute. Thereafter, based on previous literature (Bossi et al., 2017) describing a reverse J-shaped pacing strategy in ultramarathons, we analyzed the runners pacing strategy according to three different epochs (Silva et al., 2014): (1) the initial epoch, defined as the mean speed over the first 10% of the 24-h race (0 to 120 min); (2) the intermediate epoch, defined as the mean speed over the following 80% of the 24-h race (121 to 1,300 min) and; (3) the final epoch, defined as the mean speed over the last 10% of the 24-h race (1,301 to 1,440 min).

In order to accomplish the speed variations analysis, we calculated the percentage of time spent in four-speed ranges such as <3.5 km·h^{-1} (SSR), between 3.5 and 5.9 km·h^{-1} (walking speed), 6.0 and 8.0 km·h^{-1} (walk-to-running transition speed) and >8.0 km·h^{-1} (running speed). Importantly, due to the need for food, physical therapy, medical assistance, etc., athletes usually perform breaks during this challenging long-duration ultramarathon (spending time out of the track), thereby increasing the computed time and reducing the mean speed to complete a given lap. Unfortunately, the time spent at breaks during the race was unavailable in the VI Rio 24-h Marines Ultramarathon dataset, so that some estimation was required. In this regard, we determined the break periods as a substantial speed reduction (i.e., SSR) defined as a ≤3.5 km·h^{-1} speed, as the 3.5 to 6.0 km·h^{-1} range may represent a walking speed for most individuals (Rotstein et al., 2005). Moreover, a compendium of physical activities (Ainsworth et al., 2000) estimated an energy expenditure of 2.5 METs for ∼3.5 km·h^{-1} speeds (2 mph), so that completing a 400 m lap walking at this lowest speed would suggest the presence of stop(s) rather than continuous displacement. Despite the obvious limitation of arbitrarily determining break periods, this approach allowed us to take into consideration either eventual or planned breaks. Hence, the number and duration of SSR were calculated according to this criterion, thus considering the number of occurrences with mean speed <3.5 km·h^{-1} as well as the mean and total time spent at SSR (expressed as hours), respectively.

Statistics

We reported the results as mean ± standard deviation (s). After ensuring a Gaussian distribution, we analyzed pacing strategy through a 2 × 2 × 3 repeated-measures ANOVA, having performance level (HP vs. LP), sex (male vs. female) and epochs (initial, intermediate and final epoch) as the fixed factors, and subjects as the random factor. The Bonferroni *post-hoc* test was used in multiple comparisons, and the Greenhouse-Geisser epsilon was reported when the sphericity assumption was violated (Mauchly's test). Accordingly, a 2 × 2 × 4 repeated-measures ANOVA, having performance level (HP vs. LP), sex (male vs. female) and speed ranges (SSR, walking, walk-to-running transition and running) as the fixed factors, and subjects as the random factor, was used to analyze the speed variations throughout the race. The Bonferroni and Greenhouse-Geisser epsilon tests were further used. Additionally, a 2 × 2 ANOVA (sex vs. performance level) compared the total distance covered in the 24-h race, number and duration of each SSR (min) as well as the total time spent at SSR.

Pearson's product-moment correlation coefficients were used to determine the correlation between the number of SSR and the distance covered during the race. The coefficient of variation (CV) of the speed was determined by dividing the standard deviation by the mean speed with a sampling rate of 400 m. Moreover, the correlation between mean speed CV and total distance covered in 24 h was calculated, being reported together with the 95% confidence intervals. Based on the recommendations of Hopkins et al. (2009), values of $0.10 \leq r < 0.30$ indicate small, $0.30 \leq r < 0.50$ medium, $0.50 \leq r < 0.70$ large, $0.70 \leq r < 0.90$ very large, $0.90 \leq r < 1.00$ nearly perfect, and $r = 1.00$ perfect correlation. The significance level was set at 5% ($P < 0.05$). All analyses were performed using Statistical Package for Social Sciences (SPSS) version 21.0 (SPSS Inc., Chicago, Illinois, USA).

RESULTS

Overall Pacing Strategy Responses

Overall responses identified as main effects are summarized. The 2 × 2 × 3 repeated-measures ANOVA revealed an epoch main effect ($P < 0.001$) over the 24-h ultramarathon so that, regardless of sex or performance level, runners showed a faster start pace as the speed in the initial epoch was higher than speed in the second and third epochs ($P < 0.001$), but no differences were observed between the second and third epochs ($P = 0.398$). Thus, the overall pacing profile was a reverse J-shaped pacing strategy characterized by a fast start pace in the initial 10% of the race (initial epoch, 9.5 ± 1.5 km·h^{-1}), followed by a progressive decline in mean speed during the following 80% of the race (intermediate epoch, 6.2 ± 1.4 km·h^{-1}), before a non-significant endspurt in the last 10% of the race (final epoch, 6.5 ± 1.4 km·h^{-1}). Moreover, male runners ran the ultramarathon ($P = 0.000$) faster (7.92 ± 1.79 km·h^{-1}) than female runners (6.66 ± 2.18 km·h^{-1}). Accordingly, HP runners (8.25 ± 1.90 km·h^{-1}) were faster ($P < 0.001$) than LP runners (6.55 ± 1.83 km·h^{-1}).

Sex by Performance Level Interaction Effects on Pacing Strategy

Multiple comparisons revealed an interaction effect between performance level and epochs. For example, LP male runners started the race at a higher relative mean speed (144.2 ± 16.3%) when compared to HP male runners (133.2 ± 13.1%). Accordingly, LP female runners started at a higher relative mean speed (198.8 ± 24.3%) than HP female runners (149.6 ± 22.3%). Furthermore, a sex by performance level interaction effect was observed in pacing strategy. Interestingly, no difference was observed in absolute mean speed between HP male and HP female runners in the initial epoch ($P < 0.165$). However, HP male runners ran faster than female ones in intermediate ($P < 0.019$) and final epochs ($P < 0.003$). In contrast, LP male runners were faster than LP female runners in initial ($P < 0.012$), intermediate ($P < 0.000$) and final epochs ($P < 0.004$). **Figure 1** and **Figure 2** depict the pacing strategy profile of the overall 3 best male and female runners and all runners.

Regarding the time spent in different speeds, the 4 × 2 × 2 repeated-measures ANOVA showed a speed by sex interaction effect ($P < 0.004$) as well as a speed by performance level interaction effect ($P < 0.001$). Thus, overall results were that male and HP runners spent more time in running speeds (>8.0 km·h^{-1}) than female and LP runners. Accordingly, male and HP runners spent less time at SSR (i.e., speed < 3.5 km·h^{-1}) and walking speed (i.e., 3.5–5.9 km·h^{-1}) than females and LP, respectively. **Figure 3** shows the relative time spent in different speed ranges during the 24-h ultramarathon race according to performance level (panel A) and sex (panel B).

Substantial Speed Reductions Analysis

When the time spent in SSR was analyzed, a significant performance level by sex interaction effect in the number ($P = 0.037$) and total time of SSR ($P < 0.001$) was observed, but not for the mean duration of each SSR ($P = 0.067$). Overall results were that LP female runners showed an increased number of SSR when compared to HP female runners ($P < 0.001$), thereby spending a higher total time in SSR than HP female ($P < 0.001$). Furthermore, LP female runners spent a higher total time in SSR than LP male runners ($P < 0.001$). As a result, there was a significant performance level by sex interaction effect in total distance covered during the 24-h race ($P < 0.001$), as male runners ran longer distances than their female partners in HP and LP groups (**Table 1**).

Significant negative correlations were observed between the number of SSR and the total distance covered in 24 h in both male ($r = -0.47$; $P = 0.009$) and female runners ($r = -0.61$; $P = 0.003$) (**Figure 4**). Accordingly, there was a significant negative correlation between speed CV and total distance covered in 24 h, in both male ($r = -0.64$; $P < 0.001$) and female runners ($r = -0.47$; $P = 0.033$). The lowest speed variation was found in HP groups, both male (21.5 ± 4.8%; 17.1 to 25.9%) and female runners (23.1 ± 2.5%; 20.8 to 25.5%). In contrast, LP male (27.2 ± 3.0%; 24.5 to 30.0%) and female runners (28.8 ± 4.4%; 24.8 to 32.9%) showed the higher levels of CV in speed (**Figures 5A,B**).

DISCUSSION

The novel main finding of the present study suggests that the number of breaks may partially explain the 24-h ultramarathon performance as HP runners spent less time in speeds <3.5 km·h^{-1} (SSR) than LP runners. Accordingly, male runners, regardless of performance level, also showed a lower time (%24 h) in SSR than female runners. Together, both results suggest a lower time spent at very low speeds associated with active or passive resting (walking speed from 3.5 to 5.9 km·h^{-1}

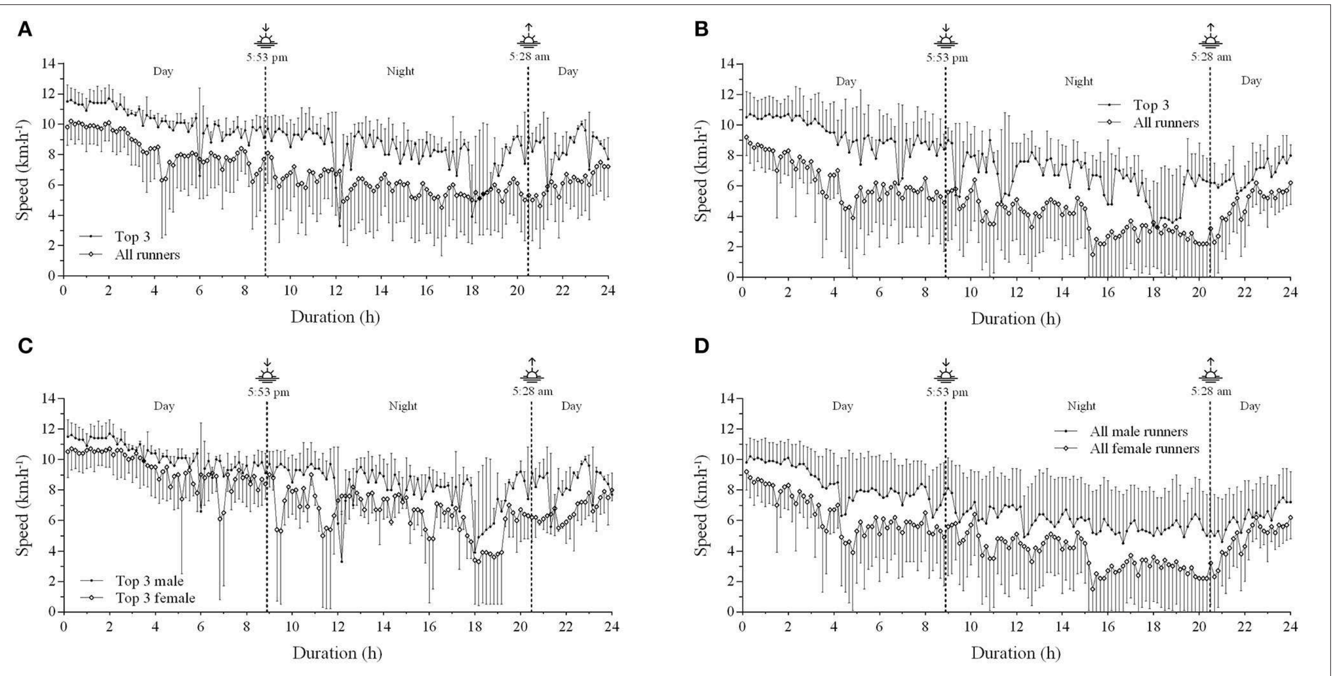

FIGURE 1 | Mean running speed in each 10-min interval of the 24-h ultramarathon. **(A)** top 3 male and all male runners; **(B)** top 3 female and all female runners; **(C)** top 3 male and top 3 female runners and **(D)** all male and all female runners; Top 3, the overall 3 best runners.

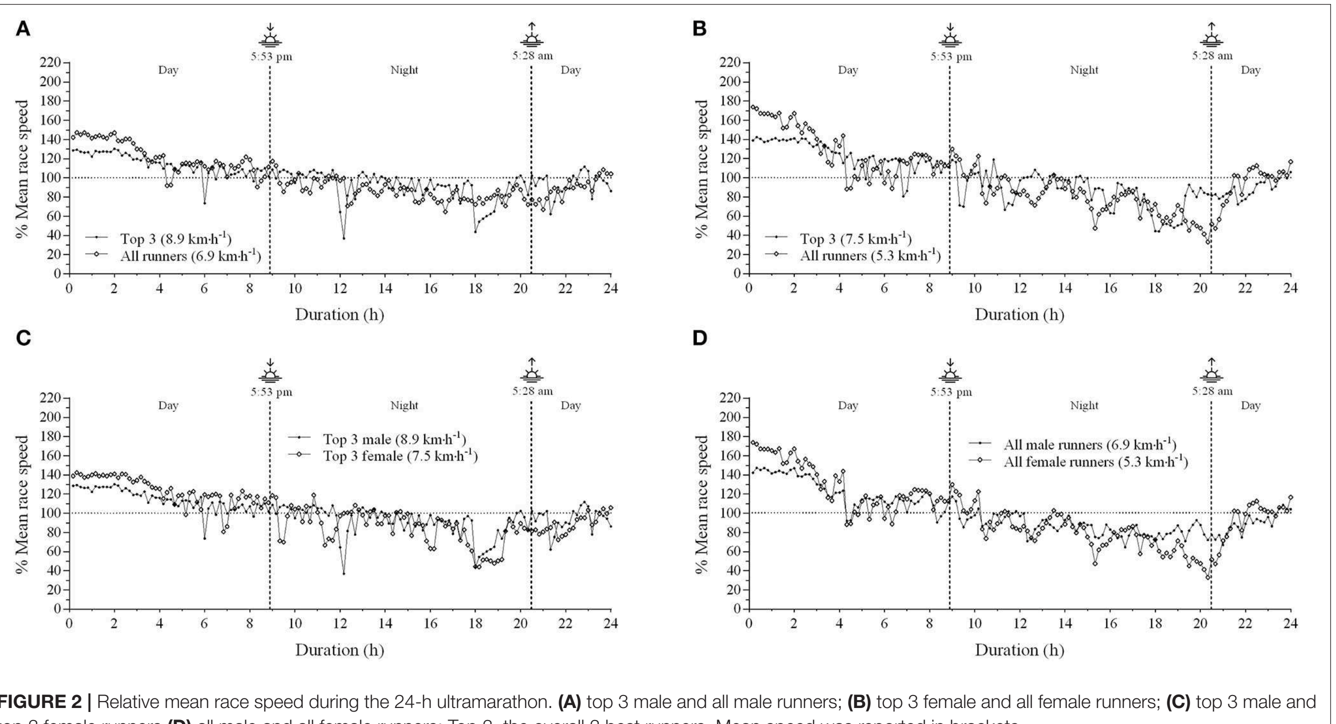

FIGURE 2 | Relative mean race speed during the 24-h ultramarathon. **(A)** top 3 male and all male runners; **(B)** top 3 female and all female runners; **(C)** top 3 male and top 3 female runners **(D)** all male and all female runners; Top 3, the overall 3 best runners. Mean speed was reported in brackets.

or SSR <3.5 km·h^{-1}) is related to better 24-h ultramarathon performance. Importantly, HP runners showed a more even pace with less speed variations than LP ones, perhaps indicating that a more conservative pacing strategy is the most appropriate to attain optimal performance in endurance events performed in extreme conditions.

In contrast to previous ultramarathon studies (Kerherve et al., 2015, 2016; Renfree et al., 2016), but confirming others

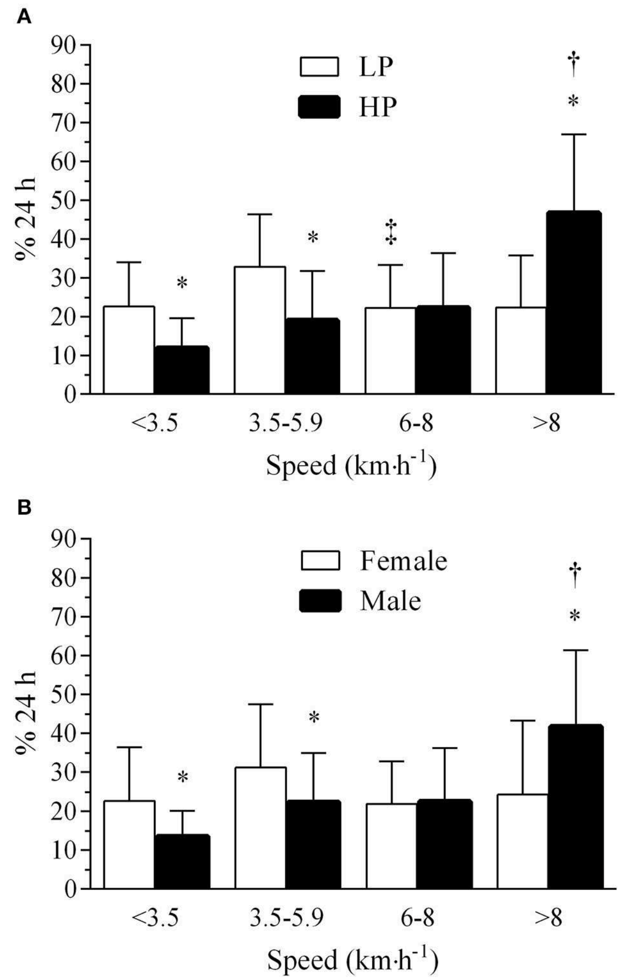

FIGURE 3 | Percentage of time spent at speeds corresponding to a substantial speed reduction (SSR <3.5 km·h^{-1}), walking (from 3.5 to 5.9 km·h^{-1}), walk-to-running transition (from 6.0 to 8.0 km·h^{-1}) and running (>8.0 km·h^{-1}). **(A)** HP vs. LP; **(B)** male vs. female; *, significant difference ($P < 0.05$) between performance levels or sexes in the same speed range; ‡, significant difference ($P < 0.05$) when compared to 3.5–5.9 km·h^{-1} LP; †, significant difference ($P < 0.05$) when compared to lower speed range(s) in the same performance level or sex; LP = low performance; HP, high performance. Results presented in mean and standard deviation.

(Bossi et al., 2017), the present study showed that runners adopted a reverse J-shaped pacing strategy during the VI Rio 24-h Marines Ultramarathon running, regardless of sex and performance level. Thus, runners slowed down the pace during most of the race, after performing a faster start and before spurting at the last 10% of the race. In this regard, HP runners sustained a higher mean speed and lower variation throughout the 24-h race than LP runners, regardless of sex differences. Importantly, both male and female HP runners used a more conservative pacing strategy, as they ran the first ∼3 h at a lower relative speed (133.2 and 149.6% of the mean speed, respectively) than LP ones (144.2 and 198.8% of the mean speed, respectively). Similar results have been found by Renfree and St Clair Gibson (2013) during the women's world championship marathon race, as they observed that underperformance was likely related to a less conservative pacing strategy, characterized by initial speeds that were unsustainable for the entire distance. Additionally, finishing times of the best athletes were closer to their personal best time performance, being the averaged speed at 98.5 ± 1.8% of the speed achieved in their personal best time performance. In contrast, athletes from the other groups showed a reduced averaged speed (at 92.4 ± 4.4%) when compared to the best runners. In our ultramarathon dataset, this more conservative pacing strategy possibly allowed racers to perform a lower number of breaks and speed variations throughout the race (as argued in the next section). Thus, one may argue that all these findings, together, suggest that conservative pacing strategies may be more adequate for different endurance running disciplines.

TABLE 1 | Total distance, number of substantial speed reductions (<3.5 km·h^{-1}), mean duration of each substantial speed reduction, total time in substantial speed reduction, and %total time (24 h) in substantial speed reduction of performance level groups and sex.

Variables	**Performance level**	
	HP	**LP**
Male	($n = 10$)	($n = 10$)
Total distance (km)	186.7 ± 18.2	149.5 ± 3.1^{a}
Number of SSR	11 ± 4	13 ± 4
Mean duration of each SSR (min)	16.9 ± 28.6	16.0 ± 23.4
Total time in SSR (h)	3.0 ± 1.7	3.5 ± 1.5
%Total time (24 h) in SSR	12.5 ± 7.1	14.6 ± 6.3
Female	($n = 7$)	($n = 7$)
Total distance (km)	162.2 ± 19.0^{b}	106.1 ± 3.7^{a,b}
Number of SSR	6 ± 3	15 ± 5^{a}
Mean duration of each SSR (min)	25.5 ± 44.8	32.1 ± 17.5
Total time in SSR (h)	2.7 ± 2.2	8.1 ± 1.5^{a,b}
%Total time (24 h) in SSR	11.3 ± 9.2	33.8 ± 6.3^{a,b}

HP, High performance; LP, Low performance; SSR, Substantial speed reduction.
[a] significant difference ($P < 0.001$) between performance levels in the same sex.
[b] significant difference ($P < 0.001$) between sexes in the same performance level. Results presented in mean and standard deviation.

Variation of Speed and the Presence of Breaks

A remarkable aspect of ultramarathon races is the high-speed variation (Parise and Hoffman, 2011; Hoffman, 2014). Accordingly, we found a high-speed variation during the VI Rio 24-h Marines Ultramarathon (**Figure 1**), which was higher than that reported by previous studies. For example, a study investigating the pacing strategy in 24 editions of a mountain 161 km ultramarathon (*Western States Endurance Run*) observed that winners showed a speed CV about 12%, while the ten best finalists were between 9 and 13% (Hoffman, 2014). Ely et al. (2008) reported that elite runners showed very little changes in 5-km pace segments during a marathon race, thus suggesting a low pace variability. In addition, Santos-Lozano et al. (2014) showed

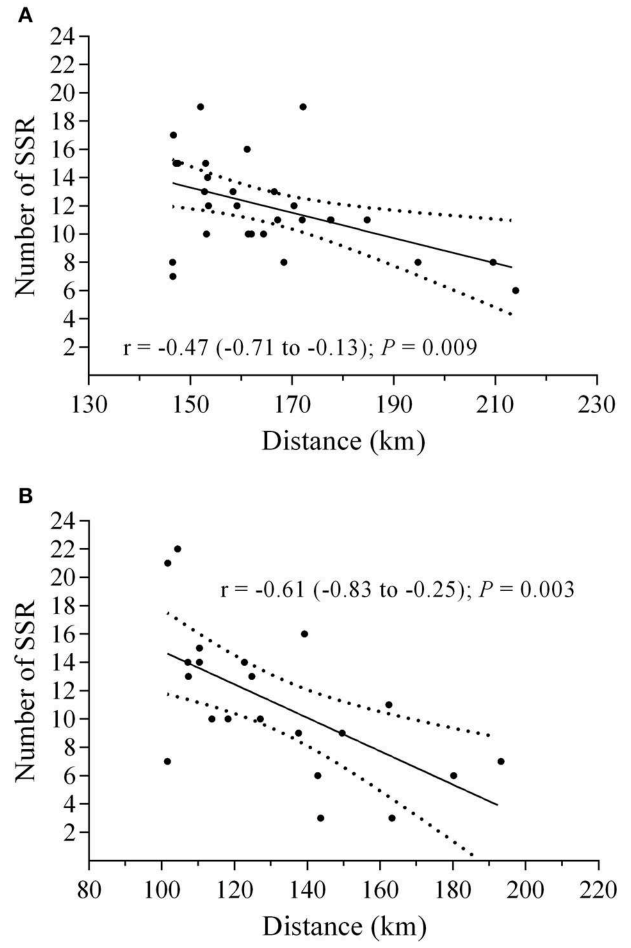

FIGURE 4 | Correlation between number of substantial speed reductions (SSR) and total distance. **(A)**, male (n = 30); **(B)**, female (n = 21).

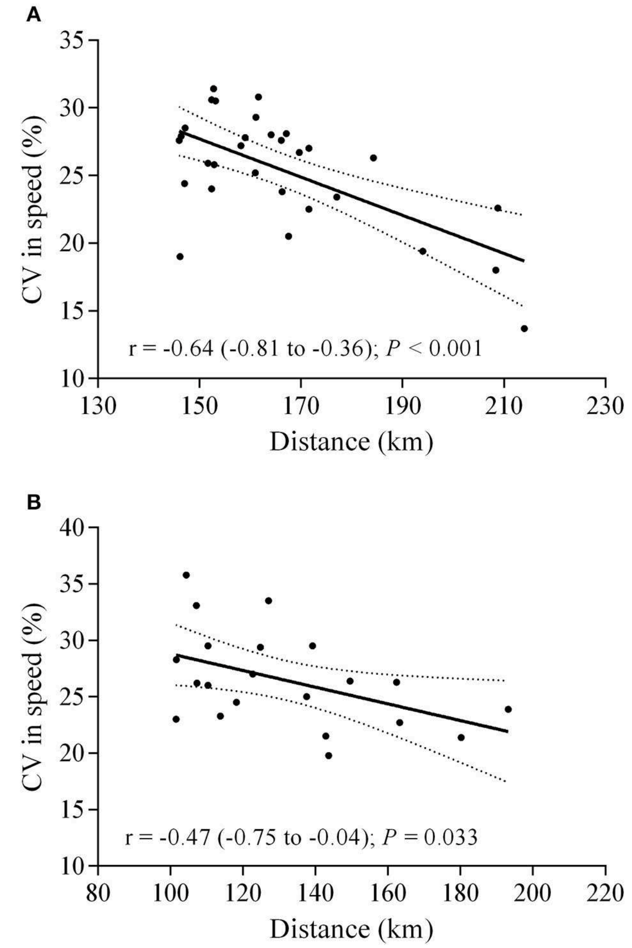

FIGURE 5 | Correlation between speed coefficient of variation (CV) and total distance. **(A)** male (n = 30); **(B)** female (n = 21).

a lower speed variability in top runners, given the 5-km splits CV ranging 6.6 to 7.8 and 8.3 to 14.4% in more and less successful runners, respectively. In this regard, an even pace profile avoiding an excessively fast start pacing strategy may be important to avoid premature fatigue as the race progresses and a decrease in speed in the second half of the race. Our CV results are similar to those of Takayama et al. (2016), as they reported that CV of speed was moderately correlated with total distance covered ($r = -0.68$; $P < 0.001$).

In the present study, we observed a speed CV ~21% for male and ~23% for female HP runners. The presence of breaks, arbitrarily defined as a mean speed <3.5 km·h^{-1} (i.e., SSR), may be related to this higher speed CV, as athletes use the SSR sections to recovery or feed themselves, as well as to take part in physiotherapy and medical assistance, etc., during a 24-h ultramarathon running. Anecdotal information indicated that most participants of the VI Rio 24-h Marines Ultramarathon believed that breaks were beneficial for performance so that they included breaks in their strategy to complete the race. However, previous literature has shown conflicting results, as Kerherve et al. (2015) reported that the lower stop total time, the better the performance in a 106 km mountain ultramarathon ($r = -0.772$; $P = 0.001$; 95% confidence interval = −1.15 to 0.39) while Kerherve et al. (2016) did not find a significant relationship ($r = -0.35$; $P = 0.21$) between stop total time and performance in a hilly terrain ultramarathon. In the preset study, we used a high-frequency split dataset and found a significant inverse correlation between the number of SSR and the total distance covered in 24 h. Taking together, previous literature and the present results may indicate that, at least to a flat terrain 24-h ultramarathon, best performance may be related to a lower number of breaks (i.e., SSR), suggesting that the maintenance of running speeds with less speed variations is beneficial to this long race. Future studies are welcome to confirm this suggestion in other ultramarathons and verify the influence of the different terrains.

Interestingly, observations of overnight vs. daytime pacing profile further suggest a possible change in pacing across the lighting-dark transition phases in the 24 h, not only in the top 3 runners but in the other runners as well, being more pronounced in the female runners. Accordingly, the SSR number was apparently higher overnight in the LP female runners. However, it is difficult to know if such an apparent nighttime-daytime pacing profile difference was due to circadian cycle variations or accumulated competition hours, as the altered pacing observed overnight may have reflected the accumulated number of hours competing. Actually, there was a more pronounced change at 9 p.m. and 3–4 a.m., thus representing an accumulation of 12 and 18–19 h of competition from the start line, respectively. Future studies are required to address to this interesting issue.

Influence of Performance Level on Pacing Strategy

Our data corroborate a recent study analyzing the influence of the performance level in pacing strategy during a 100 km ultramarathon (Renfree et al., 2016). The best performance group raced the first 30 km at lower relative speeds when compared to other groups in the first three 10-km segments (all $P < 0.01$). In addition, our results corroborate with findings by Bossi et al. (2017), who showed that the fastest runners showed a more conservative initial speed (initial 3 h of the race), before slowing down as the competition progressed. In contrast, slower runners were unable to maintain their initial speed as much long as the fastest runners, thereby reducing their mean speed in a higher extension. Similar results were reported for elite marathon runners during the women's World Championships marathon in 2009 (Renfree and St Clair Gibson, 2013), as runners finishing the race in the first quartile raced the first two 5 km segments at a slower relative speed when compared to those finishing the race between the second and the fourth quartile. Esteve-Lanao et al. (2014) described the pacing distribution of 768 male runners participating from 2007 to 2013 of the world cross-country championships. Groups of 10 participants according to final position (1st to 10th, 11th to 20th, etc.) were considered. They reported that top-10 finishers in the world cross-country championships elicited an even pace rather than other finishers that used a fast-to-slow pacing strategy pattern, consequently, a much more stable pacing pattern should be considered to maximize the final position. With the purpose to examine pacing among 48 male runners who ran more than 161 km in a 24-h ultramarathon, Takayama et al. (2016) divided runners into five groups (A: 1st−10th, B: 11th−20th, C: 21th−30th, D: 31th−40th, and E: 40th−48th). The 24-h distance within the various groups ranged from 238.38 ± 11.41 km for group A to 164.14 ± 2.49 km for group E. Group A runners ran at a relatively constant speed (>8 km·h^{-1}) during the second half of the race, whereas the corresponding pace was slower (<6 km·h^{-1}) for other groups.

In the present study, we observed a slower relative speed at the initial ∼3 h of the race in HP than in LP runners, regardless of sex. Possibly, this more aggressive pacing strategy may have been related to a decreased performance in LP runners, as the maintenance of a greater initial relative speed along the race may have been unsustainable. Thus, the selection of a more aggressive start pacing strategy may have led LP runner to reduce the mean speed and possibly perform more SSR. Consequently, these results provide important considerations for coaches and athletes competing in endurance events, as they may suggest that an aggressive start pacing strategy as performed by LP runners is possibly inadequate. For athletes competing in different IAAF running disciplines, one may suggest that the adopted pacing strategy has a major influence on the final achievement, and a more conservative pattern is advised. Furthermore, this result is different from that reported by Lima-Silva et al. (2010) during a simulated 10 km running race, as the LP runners investigated in that study started the running race with a more conservative pacing strategy when compared to HP runners. However, it is worth to suggest caution when comparing both studies, given the difference in distance and duration between a 24-h ultramarathon running and a 10 km running race (Lima-Silva et al., 2010). For example, a 10 km running race is as long as only ∼3% of a 24-h ultramarathon race, thus suggesting long-term races represent a different psychophysiological challenge for the athlete.

Differences of Sex in Pacing Strategy

Recently, Bossi et al. (2017) showed that athletes adopted a reverse J-shaped pacing strategy in a 24-h ultramarathon, with low deviations from the mean speed during most of the race and the presence of an endspurt in the last hours (despite slight reductions). Accordingly, we found an increased speed in LP and HP groups in the last hour, however, while female runners increased the speed throughout the last 10% of the race, male runners showed a variable endspurt according to the performance level (LP male runners spurted throughout the last 10% of the race and HP runners slowed down the pace in the last 30 min of the endspurt phase). The reason for this discrepancy between studies is not clear (Bossi et al., 2017). Perhaps the higher data sampling frequency used in the present study may have allowed us to identify this difference in pacing strategy.

A study by Renfree et al. (2016) reported that women demonstrated lower initial relative speeds when compared to men. It is possible that the decision for a higher initial speed in female runners in the present study has been influenced by the speed imposed by male runners since both men and women started the ultramarathon race at the same time. This suggestion is based on the "herd principle," that the most likely decision that an athlete could make about the selection of an initial pace during a competitive event is simply to follow the behavior of direct competitors, as shown in 4 km time trials raced against opponents (Konings et al., 2016). Likewise, such a "herd principle" may be present in findings reported by Renfree and St Clair Gibson (2013) in women World Championship marathon race as well as Hanley (2014) and Esteve-Lanao et al. (2014) in IAAF World Cross Country Championships.

LIMITATIONS

Two obvious limitations of the present study were related to the SSR calculation. First, the absence of information related to planned or eventual SSR may limit our interpretations, as we were unable to correlate some behaviors normally linked to breaks in a pacing strategy perspective (such as planned meal, physiotherapy, etc.). Second, the use of an arbitrary criterion to identify periods of break may be also considered as a limitation, as some reductions in mean speed may have been inadequately identified as a break; in contrast, they may indicate a substantial speed reduction without a complete break. However, most behaviors such as feeding may be still accomplished at a very slow walk, so that the SSR strategy used in the present study may be an indication of how SSR may impact 24-h ultramarathon pacing strategies. The choice of speed threshold was based on previous papers of human locomotion (Yokoyama et al., 2016; Fokkema et al., 2017). The selection of slow speed walk of 4 $km \cdot h^{-1}$ as reported elsewhere (Yokoyama et al., 2016), was important to make the identification of a SSR possible. Another limitation is the absence of knowledge regarding the experience and training level of the runners.

Practical Applications

The findings of the present study may be used by coaches and athletes to plan and develop more effective pacing strategies for ultramarathon races. For example, they indicate that starting an extreme endurance race at a lower percentage of the mean speed, thus decreasing the difference between the initial and the mean speed that could be sustained throughout the race may be beneficial for long-term race performance. Mainly in ultramarathon races, a more conservative pace maintaining a mean speed with lower variation allows the avoidance of a number of substantial speed reduction during the race (i.e., SSR, speeds <3.5 $km \cdot h^{-1}$) and increasing the time in running speeds >8.0 $km \cdot h^{-1}$), may improve performance in 24-h ultramarathons. Therefore, feeding, clinical assistance, and other behaviors could be planned in a pacing strategy scenario that considers this information.

The results of the present study may be applicable to ultramarathon runners having a similar performance level. We worked on a public dataset of 140 runners competing the VI Rio 24-h Marines Ultramarathon race and unfortunately, no data to characterize them was available. Study by Knechtle et al. (2011) reported anthropometric and training experience of recreational ultramarathon runners completing 146.1 ± 43.1 km in a 24-h ultramarathon in Basel, Switzerland (2008 to 2010). In contrast, Takayama et al. (2016) analyzed the best 48 male runners who ran more than 161 km in a 24-h ultramarathon in Tokyo, Japan (2014), as a contest to select members of Japan's national team for the world championships. Runners completed from 258.7 to 164.1 km in this later ultramarathon. In the present study, most of the male runners completed from 148 to 192 km while most female ones completed from 100 to 160 km. Consequently, one may argue that our pacing strategy results are directly applicable to recreational runners, similar to those investigated by Knechtle et al. (2011). Future studies may confirm these results in ultramarathon runners having a performance level similar to those athletes investigated by Takayama et al. (2016).

Results of the present study may also provide insights into the 2019 IAAF World Championship in Qatar regarding a physiological and psychological highly-demanding, given the likely hot temperatures and potentially high humidity levels found in September and October that may eventually impair performance in endurance events. Despite this 2019 Championship will not run Ultramarathon and Mountain Running races in its timeline, high temperatures and humidity levels may probably push the human body limits in Marathon and 50 km Race Walk competitions toward those usually seen in ultra-long running. For example, the reversed-J pacing strategy observed in the present ultramarathon dataset may likely indicate that athletes competing in these races.

CONCLUSION

Regardless of sex and performance level, runners used a reverse J-shaped pacing strategy during a 24-h ultramarathon race. Importantly, male and female HP runners showed that a conservative pacing strategy, with lower speeds in the beginning and higher speeds toward the end (avoiding substantial speed reductions such as SSR), may be the most adequate for different endurance running disciplines. These results also show that different competition dynamics between men and women warrant further exploration, given the possibility of a "herd principle."

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the Hospital Naval Marcílio Dias. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

AI, TS, FH, DA, BV, BT, and FP have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Meteorological Risks in Doha 2019 Athletics World Championships: Health Considerations From Organizers

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The Doha 2019 IAAF World Championships represent a challenge for athletes, workforce and spectators who could compete, work or attend under likely extreme meteorological conditions. This short article summarizes the methodology used by the IAAF and the Local Organizing Committee doctors to analyze and reduce risks, while complying as much as possible with existing recommendations or policies. The main steps to be completed are identification and description of weather-related risks, description and whenever possible testing of all their possible mitigation measures during test events, revision of these risks once mitigation implemented, and finally drafting a contingency plan for remaining exceptional and impactful occurrences. Such risk management methodology could apply to other sports, ideally from the host city selection to the delivery of the competitive event.

Keywords: athletics, risk, mitigation, contingency, heat-related illnesses, meteorologic condition

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INTRODUCTION

On November 2014, the International Association of Athletics Federations (IAAF) Council voted and chose the city of Doha (Qatar) to host the IAAF World Championships in 2019. The Qatari officials supporting this bid had already failed 2 years earlier and the 2017 IAAF World Championships were finally attributed to London. Although the IAAF Council debates remain undisclosed, it is likely that the proposal of shifting World Championships to late September–early October instead of August on one hand, and a refurbished air-conditioned Khalifa stadium (May 2017) on the other hand, probably helped the Qatari officials to finally obtain the organization of the 2019 IAAF World Championships[1]. However, organizing a major sporting event in Qatar during the fall remains a challenge from a climatic perspective (Hosokawa et al., 2018b). Indeed, some Athletics endurance events, such as race walk and marathon competitions cannot be organized in an air-conditioned stadium, and therefore potentially expose athletes and staff to significant risks of heat-related illnesses.

SECTIONS ON POLICY OPTIONS AND IMPLICATIONS

In order to guide member federations and Athletics competition organizers to provide suitable health care for athletes in and out of competition, the governing body of Athletics relies on

[1] https://www.iaaf.org/news/press-release/iaaf-evaluation-commission-candidates-2019-ia

TABLE 1 | The actual WBGT coding system described in the IAAF competition medical guidelines.

Wet bulb globe temperature (WBGT) index flag coding system	WGBT	Recommendations	
Black flag	Extreme	>28°C (>82°F)	Consider rescheduling or delaying the event until safer conditions prevail; if the event must take place, be on high alert
Red flag	High	23–28°C (73–82°F)	Everyone should be aware of injury potential; individuals at risk should not compete
Yellow flag	Moderate risk	18–23°C (65–73°F)	Risk increases as event progresses through the day
Green flag	Low	<18°C (<65°F)	Risk low but still exists on the basis of risk factors

Competition Medical Guidelines[2]. The guidelines' objectives are about providing appropriate and permanent medical care that will help athletes to reduce their risk of suffering from injuries and illnesses, and responding promptly to medical emergency situations. This document also provides guidance in designing the necessary services in order to offer excellent medical coverage to team officials, spectators and other members of the Athletics' family. Competition Medical Guidelines are not of mandatory application for the Local Organizing Committee (LOC) but are recommended to be followed. They serve, prior to and during the event, as a platform of discussion between the IAAF medical delegate and the chief medical officer from the LOC, should some country-specific adjustments need to be performed.

The IAAF Competition Medical Guidelines, chapter 3, paragraph 4.2 specifically deals with weather conditions. For the purpose of these guidelines, Wet Bulb Globe Temperature (WBGT) is used and calculated as follow:

$\mathrm{WBGT} = 0.7\ \mathrm{WBT} + 0.2\ \mathrm{BGT} + 0.1\ \mathrm{DBT}$, where WBT, BGT, and DBT are wet bulb, black globe and dry bulb outdoor temperature, respectively (Yaglou and Minard, 1957).

A corresponding colored flag system can then be used to visually signal the thermal injury risk of current weather conditions to competitors and spectators (**Table 1**). For instance, a black flag means an extreme risk and corresponds to WBGT above 28°C. A red flag means a high risk and corresponds to WBGT between 23 and 28°C.

Although this goes beyond the scope of this article, one must acknowledge that the use of WBGT in exercise and occupational physiology is debated (Budd, 2008; Brocherie and Millet, 2015). Indeed, there are some conceptual limitations in the WBGT as, for instance, it does not consider a possible restriction of sweating, the type of clothing and more importantly the level of endogenous caloric production associated with exercise.

Dealing with weather conditions, the IAAF guidelines also recommend that LOC medical and competition functional units should work together with the IAAF medical delegate to monitor weather conditions and that a specific contingency plan should be implemented to consider the scenario of extreme meteorological situations, that could force a delay or even a cancellation of the competition.

ACTIONABLE RECOMMENDATIONS

As described below, there are four recommendations which should be actioned in the following order:

1. Assess the meteorological risks (definition, impact, and likelihood).
2. Set up a meteorological risks' mitigation strategy.
3. Reassess risks following implementation of the mitigation strategy.
4. Draft a contingency plan which addresses significant residual risks.

Assessment of the Meteorological Risks

In Doha (Qatar), during fall, there are two types of adverse meteorological conditions to be considered. The first and main risk is represented by extremely hot and/or humid conditions. The second risk is the occurrence of dust storms.

Hot and humid weather conditions are represented in **Table 2**[3]. During late September and early October, mean WBGT is expected to be above 28°C (black flag) between 7 a.m. and 5 p.m. Should a heat wave (at least 2 consecutive days with unusually high level of air temperature) occur, this black flag period can be extended from 6 a.m. to midnight. During this period of the year, relative humidity is also expected to be from moderate to high, with the highest levels observed between 6 p.m. and 8 a.m.[4] This relative humidity profile is negatively correlated with the level of solar exposure and radiation. From a thermoregulatory perspective, this is a dilemma since organizers must choose between the lesser of two evils; in this case high relative humidity.

Dust storms are quite frequent in Qatar. The numerous deserts which engulf the Qatari peninsula represent infinite supplies of airborne solid particles, such as dust and sand. These spectacular phenomena associated with wind gusts, can carry large amounts of dust, with the leading edge being composed of a wall of thick dust as high as 1.6 km (Bartlett, 2004). In addition of their deleterious effects on visibility, engines, and electronic devices, exposure of human beings to desert dust include immediate increased respiratory symptoms and worsening of the lung function in individuals with asthma (Goudies, 2014). Acute *keratoconjunctivitis sicca* ("dry eyes") can also occur in such circumstances (Goudies, 2014). In the Qatari area, these dust storms are called "*shamal*." According to Bartlett (2004), "*shamal*" events mostly occur between March and September with a peak around May. In late September–early October, the

[2]IAAF Competition Medical Guidelines: Available online at: https://www.iaaf.org/about-iaaf/documents/health-science

[3]https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/

[4]https://weatherspark.com/m/105083/10/Average-Weather-in-October-in-Doha-Qatar#Sections-Humidity

TABLE 2 | Risk assessment based on modern-era retrospective analysis for research and applications (MERRA-2) dataset recorded in Doha between 1980 and 2016.

Hour (Local Standard Time)	WBGT (°C)				Corresponding flag color (IAAF competition medical guidelines; 2013)			
	Min	Max	Mean	Mean + 1sd	Min	Max	Mean	Mean + 1sd
0	20.0	28.1	24.7	26.2	Yellow	Black	Red	Red
1	19.9	27.9	24.6	26.0	Yellow	Red	Red	Red
2	19.8	27.8	24.4	25.9	Yellow	Red	Red	Red
3	19.6	27.6	24.3	25.8	Yellow	Red	Red	Red
4	19.5	27.6	24.2	25.7	Yellow	Red	Red	Red
5	19.4	27.7	24.1	25.7	Yellow	Red	Red	Red
6	21.0	32.9	26.2	28.0	Yellow	Black	Red	Black
7	24.2	35.5	28.6	30.2	Red	Black	Black	Black
8	25.7	37.3	30.2	31.9	Red	Black	Black	Black
9	26.6	37.2	31.7	33.4	Red	Black	Black	Black
10	27.1	39.0	32.7	34.5	Red	Black	Black	Black
11	27.3	41.1	33.2	35.1	Red	Black	Black	Black
12	27.4	44.8	33.3	35.3	Red	Black	Black	Black
13	27.1	39.1	33.0	34.8	Red	Black	Black	Black
14	26.6	37.3	32.3	34.0	Red	Black	Black	Black
15	25.7	35.6	31.2	32.8	Red	Black	Black	Black
16	24.1	33.5	29.5	31.1	Red	Black	Black	Black
17	21.9	31.4	27.3	28.8	Yellow	Black	Red	Black
18	21.0	30.4	26.5	28.0	Yellow	Black	Red	Black
19	20.5	29.8	26.0	27.5	Yellow	Black	Red	Red
20	20.2	29.4	25.6	27.1	Yellow	Black	Red	Red
21	19.9	29.0	25.3	26.8	Yellow	Black	Red	Red
22	19.7	28.7	25.0	26.6	Yellow	Black	Red	Red
23	19.5	28.5	24.8	26.3	Yellow	Black	Red	Red

Hours are given in Local Standard Time and Min, Max, and Mean temperatures are expressed as average of values recorded between the 27th of September and the 7th of October (dates of the IAAF World Championships).

monthly average occurance of "*shamal*" days is <2. Moreover, the most likely time of the day in terms of occurrence is 10 a.m. with mean duration of 4 h. However, the maximal duration can be up to 10 h which would possibly jeopardize race preparation and its execution. The wind associated with these events can be strong, but their average speed is 7.5 m/s.

The impact of a high WBGT on athlete is potentially very high. It goes from the benign consequences, such as exercise-associated muscle cramp and reduction in performance, to more serious medical conditions, such as heat exhaustion and exertional heat stroke (Epstein and Yanovich, 2019). Indeed, the most serious condition to occur is exertional heat stroke which can ultimately lead to death of athlete or staff if not properly and timely diagnosed and managed (Navarro et al., 2017; Hosokawa et al., 2018a). To a lesser level of gravity, heat stress is also associated with impaired athletic performance, especially in middle and long distance running and race-walking competitions (Guy et al., 2015). LOC volunteers or spectators, if exposed to heat for a long period of time (directing spectators or athletes, queuing), could suffer from non-exertional heat stroke.

In an Athletics competition setting, the impact of a dust storm is limited. Indeed, a healthy athlete could experience at most an asthma exacerbation, pulmonary symptoms, and conjunctivitis. Consequence of such a storm, which cannot be mitigated by using a protective mask, might be worst for unfit staff or workforce. This could prevent the individual from competing/working but is unlikely to represent a life-threatening condition. Conversely, potential impact on the competition logistic is very high. It could also seriously damage electronic devices that are used for timing, communication and broadcasting purposes as well as temporary installation, such as tent, banners, scaffoldings. The Khalifa stadium, which is not a fully covered stadium will be affected by a dust storm. Therefore, competitions held in this arena will have to be postponed for 12–24 h waiting for the end of the episode and the complete cleaning of the field of play. The Khalifa ventilation/air conditioning system is protected from this sand/dust and pathogen contamination by a complex system of progressive air filtering.

The likelihood of a high WBGT was calculated from the climatological data provided by the Qatari Civil Aviation Authority. In order to make the calculation of the cumulative distribution function, we have checked that temperatures recorded and provided by the Qatari Civil Aviation Authority, during 24 h in fall in Doha are normally distributed. Then, using the dataset reported in **Table 2**, the probability of a mean (calculated on 1 h) WBGT above 23°C WBGT is extremely high (>99.9%) between 7 a.m. and 5 p.m. A probability for a temperature above 28°C WBGT is high (64.6%) between 7 a.m. and 5 p.m.

Dust Storm

Dust storms are not frequent in late September–early October. Indeed, when the whole Qatari territory is considered, their occurrence is ~1.4 days per month (somewhere in the country) during that period of the year. Moreover, new meteorological models can predict these storms within a 48–72 h in advance (Bartlett, 2004). However, the 10 days duration of the Athletics World Championships increases this risk, which remains however low.

Meteorological Risks Mitigation Strategy

A risk mitigation strategy, by definition, should take steps to reduce the risks components, i.e., their probability of occurrence and their impact.

One of the very first measures potentially to reduce the likelihood of high WBGT is to have most of the Athletics events organized in the Khalifa stadium, which is a unique stadium with an air conditioning system. Indeed, the ventilation system of this open stadium can be adjusted to WBGT as low as 20°C, while the outdoor WBGT is above 35°C. Unfortunately, race walking events and marathons cannot be held in stadium and cannot benefit from this revolutionary air conditioning system, which controls not only ambient temperature but also relative humidity. Therefore, shifting the dates of the World Championships from August to late September–early October has been the second mitigation measure proposed by the Qatari organizers to the IAAF. A third measure adopted by the IAAF was to propose to change the habitual competition timetable. As a result, all morning session were canceled and only evening sessions (heats and finals) were planned. Although the stadium has an air conditioning system, which will be set up between 23 and 25°C WBGT, the warm-up and training areas nearby (Aspire Zone) do not propose similar thermal conditions for all athletes, especially for distance runners and long throwers (discus, hammer throw, javelin). The most innovative measure (never used in any previous World Championships) was probably to move the start time of endurance events like marathons and race-walking competition very late at night (**Table 3**). Indeed, these events are usually planned early morning, between 6 and 9 a.m. during most of the IAAF World Championships. A quick look at **Table 2** shows that this was not possible in this case, as most, if not all, of these events would have been initiated under black flag conditions, with a rising air temperature. An alternative solution would have been to start these events at 7 p.m., but the IAAF Health and Science Department advised its Competition Department and the LOC to take a safer approach and finally agreed on a start time after 11:30 p.m.

An important measure taken to reduce the impact of high WBGT is to set up an education and communication campaign in the direction of athletes, their supporting staff as well as volunteers and workforce. This communication plan is achieved through various means, such as conferences for doctors, coaches and athletes, IAAF's circular letters to its member federations, electronic and printed leaflets[5] distributed by the IAAF (including through its website) and the LOC. The main topics addressed in this campaign are:

- The anticipated climatic condition in Doha during the World Championships,
- Basic notion of thermoregulation in exercising individuals,
- How does heat impair health and performance,
- The importance of hydration (qualitative and quantitative aspects) and how to identify dehydration,
- How and when to heat-acclimatize,
- Description and benefits of main pre- and per-cooling methods.
- Additional heat-illness risk factors, such as consumption of stimulants, diuretics, and non-steroidal anti-inflammatory drugs

Another set of mitigation actions to reduce the impact of high WBGT, consisted of secondary prevention measures. These are mainly for health professionals, involved in the World Championships medical plan (national teams and LOC). Some of the team doctors, physiotherapists, nurses and athletic trainers were offered to attend continuing educational meetings and practical workshops organized by the IAAF Health and Science Department and the International Institute for Race Medicine[6]. This educational program contains pedagogical material that specifically deals with heat-related medical condition diagnoses and management. Similarly, all LOC health professionals underwent similar education session under the supervision of the LOC chief medical officer. Finally, extensive preparation work was done to build and organize high end medical stations on the site of the competitions. Exertional heat stroke represents the most serious medical condition that the medical staff could have to early diagnose and treat on the competition site, as an immediate transfer to an hospital setting is not recommended (Flouris et al., 2015). Indeed, heat stroke patients (core temperature above 40.5°C at the time of the collapse) should be immediately immersed in ice bath (water temperature below 10°C) while monitoring the decrease of their core temperature through a rectal thermistor (Flouris et al., 2015) This the reason why the Corniche main medical station, where marathons and race-walking events are planned were voluntarily oversized and overequipped to host and treat on site (including serious heat-related illnesses) a maximum of twenty four athletes in a 1-h period. The maximal number of athletes competing at the same time is 80 in the 50 km race walking men and women. This ratio between the number of medical and the number of athletes on the race course has never existed in any previous IAAF World Championships. The marathon races are run on seven laps of 6,027 m. Twenty and 50 km race walks use the appropriate number of 1 and 2 km laps, respectively. As all these laps are the two sideways of a main (Corniche) coastal road, surveillance, alert, and intervention of the medical staff, and transfer to secondary of main medical settings is very fast and facilitated.

Deciding to hold the World Championships in late September–early October, as well as holding the competitive events in the evening, when these phenomena are at their minimum occurrence rate, is the only option which was taken by both the LOC and the IAAF to reduce the likelihood of dust storms.

Regular contacts between the LOC and the Qatari meteorological authorities are fundamental. Although the impact of a dust storm on athlete is limited, the consequences on other sectors of the organization for which visibility and sensible electronic material are important (broadcasting, timing, marketing, security) can be quite significant but are beyond the scope of this article.

Reassessment of Risks Following Implementation of the Mitigation Strategy

As shown in **Table 3**, start time for all the endurance events organized out of the air-conditioned Khalifa stadium has been set between 11:30 p.m. and midnight. This was decided following a new calculation of the likelihood of high WBGTs with these new schedules. Recalculating the cumulative distribution function (**Table 2**), the likelihood of facing a red flag at midnight (approximate start time) during marathons or race walk events of the World Championships is very high at 87%. However, a start can be given under a red flag condition. Similarly, the likelihood of facing a black flag at midnight during marathons or race walk events is ~2.4%. Giving a start under black flag condition can be problematic as it is not in accordance with the IAAF Competition Medical Guidelines, expose athletes to heat-related illnesses, and decreased performance. One can see here that moving the endurance race start time from 7 a.m. to

[5]Beat the Heat Leaflet: Available online at: https://www.iaaf.org/about-iaaf/documents/health-science

[6]International Institute for Race Medicine: Available online at: https://www.racemedicine.org/

TABLE 3 | Doha 2019 World Championships timetable (partial).

Day 1–Friday, 27 Sep				**Day 2–Saturday, 28 Sep**				**Day 3–Sunday, 29 Sep**				**Day 4–Monday, 30 Sep**			
16:30	Long Jump	M	Q A + B	16:15	Discus Throw	M	Q A	*19:40*	*50 km RW*	*W*	*MC*	16:30	Javelin Throw	W	Q A
16:35	100 m	M	Prelim	16:30	100 m	W	R1	*19:45*	*50 km RW*	*M*	*MC*	17:05	200 m	W	R1
16:40	Hammer Throw	W	Q A	17:05	800 m	M	R1	*19:50*	*Hammer Throw*	*W*	*MC*	18:00	Javelin Throw	W	Q B
17:10	800 m	W	R1	17:30	Pole Vault	M	Q A+B	20:05	200 m	M	R1	18:20	400 m	W	R1
17:30	Pole Vault	W	Q A + B	17:45	Discus Throw	M	Q B	20:40	Pole Vault	W	Final	*19:10*	*20 km RW*	*W*	*MC*
18:05	100 m	M	R1	18:05	400 m H	M	SF	*21:05*	*10,000 m*	*W*	*MC*	*19:15*	*Pole Vault*	*W*	*MC*
18:10	Hammer Throw	W	Q B	18:45	100 m	M	SF	21:20	100 m	W	SF	*19:20*	*4 × 400 m Relay*	*X*	*MC*
18:40	High Jump	W	Q A + B	*19:05*	*Marathon*	*W*	*MC*	21:45	Triple Jump	M	Final	*19:30*	*Triple Jump*	*M*	*MC*
19:00	3,000 m SC	W	R1	19:15	800 m	W	SF	21:55	800 m	M	SF	*19:35*	*100 m*	*W*	*MC*
19:25	Triple Jump	M	Q A + B	19:25	Hammer Throw	W	Final	*22:20*	*Long Jump*	*M*	*MC*	20:05	110 m H	M	R1
19:55	5,000 m	M	R1	20:00	4 × 400 m Relay	X	R1	22:35	4 × 400 m Relay	X	Final	20:30	High Jump	W	Final
20:30	400 m H	M	R1	20:40	Long Jump	M	Final	*22:40*	*100 m*	*M*	*MC*	20:50	200 m	M	SF
				21:10	10,000 m	W	Final	23:20	100 m	W	Final	21:20	5,000 m	M	Final
				22:15	100 m	M	Final					21:25	Discus Throw	M	Final
												21:50	3,000 m SC	W	Final
Day 1–Friday, City, 27-28 Sep				**Day 2–Saturday, City, 28-29 Sep**				**Day 3–Sunday, City, 29-30 Sep**				22:10	800 m	W	Final
tbc	*Opening*			23:30	50 km Race Walk	W	Final	23:30	20 km Race Walk	W	Final	22:40	400 m H	M	Final
23:59	Marathon	W	Final	23:30	50 km Race Walk	M	Final								
Day 6–Wednesday, 2 Oct				**Day 7–Thursday, 3 Oct**				**Day 8–Friday, 4 Oct**				**Day 9–Saturday, 5 Oct**			
16:35	100 m Dec	M		16:35	110 m H Dec	M		*19:45*	*Shot Put*	*W*	*MC*	16:30	Javelin Throw	M	Q A
16:45	Shot Put	W	Q A + B	16:40	Triple Jump	W	Q A + B	*19:50*	*400 m*	*W*	*MC*	17:15	100 m H	W	R1
17:05	100 m H Hep	W		17:30	Discus Throw Dec	M	A	20:10	1,500 m	M	SF	*17:25*	*400 m H*	*W*	*MC*
17:30	Long Jump Dec	M	A + B	*17:50*	*200 m*	*W*	*MC*	20:15	High Jump	M	Final	17:30	400 m	M	MC
17:35	1,500 m	W	R1	18:15	Long Jump Hep	W	A + B	20:40	4 × 100 m Relay	W	R1	17:50	Long Jump	W	Q A + B
18:00	Discus Throw	W	Q A	18:35	Discus Throw Dec	M	B	*20:50*	*Heptathlon*	*W*	*MC*	18:00	Javelin Throw	M	Q B
18:10	*Pole Vault*	*M*	*MC*	19:05	Pole Vault Dec	M	A	21:00	Discus Throw	W	Final	*19:05*	*Discus Throw*	*W*	*MC*
18:15	High Jump Hep	W	A + B	*19:15*	*Hammer Throw*	*M*	*MC*	21:05	4 × 100 m Relay	M	R1	*19:10*	*20 km RW*	*M*	*MC*
18:25	5,000 m	W	R1	19:20	Shot Put	M	Q A	21:30	400 m H	W	Final	19:55	4 × 400 m Relay	W	R1
18:50	Shot Put Dec	M	A + B	20:05	Pole Vault Dec	M	B	21:45	3,000 m SC	M	Final	20:05	Shot Put	M	Final
19:15	*800 m*	*M*	*MC*	20:10	Javelin Throw Hep	W	A + B	*21:55*	*Decathlon*	*M*	*MC*	20:25	4 × 400 m Relay	M	R1
19:25	Discus Throw	W	Q B	20:40	Shot Put	M	Q B	22:20	400 m	M	Final	20:35	Triple Jump	W	Final
20:05	110 m H	M	SF	*21:40*	*110 m H*	*M*	*MC*	*22:25*	*3,000 m SC*	*M*	*MC*	20:55	1,500 m	W	Final
20:25	*Javelin Throw*	*W*	*MC*	22:00	1,500 m	M	R1	*22:30*	*High Jump*	*M*	*MC*	21:25	5,000 m	W	Final
20:30	Shot Put Hep	W	A + B	22:05	Javelin Throw Dec	M	A					*21:55*	*Shot Put*	*M*	*MC*
20:35	400 m	M	SF	22:35	Shot Put	W	Final					22:05	4 × 100 m Relay	W	Final
20:40	High Jump Dec	M	A + B	23:00	1,500 m	W	SF					22:15	4 × 100 m Relay	M	Final
21:05	400 m H	W	SF	23:10	Javelin Throw Dec	M	B					*22:20*	*1,500 m*	*W*	*MC*
21:30	200 m	M	MC	23:50	400 m	W	Final								
21:40	Hammer Throw	M	Final	00:05	800 m Hep	W	Final								
21:50	200 m Hep	W		00:25	1,500 m Dec	M	Final								
22:35	200 m	W	Final					**Day 8–Friday, City, 4-5 Oct**				**Day 9–Saturday, City, 5-6 Oct**			
22:55	110 m H	M	Final					23:30	20 km Race Walk	M	Final	23:59	Marathon	M	Final
23:15	400 m Dec	M													

Italic values represent Medal Ceremony (MC). Gray shades highlight the timing of endurance events held at the Corniche: Race Walks and Marathons.

midnight is a very efficient mitigation measure that reduces the likelihood of a cancellation or a rescheduling associated with a black flag. Indeed, this probability moves from 64.6% down to 2.4%, whereas it modestly affects the risk linked to a red flag (from almost 100% to 87%).

Draft a Contingency Plan Which Addresses Significant Residual Risks

In the rare occurrence of a WBGT above or equal to 28°C at the start of marathons or race-walking events, a contingency plan could be implemented. Here below are very brief descriptions of practical measures that the LOC and the IAAF Competition and Medical Directors could take. For all below events, a major measure would be to stop all athletes still competing on the race course after 6:15 a.m., since a significant rise in WBGT occurs after this time (**Table 2**). This also means that if postponing the start of the competition is considered, the expected chronometric performance of an average elite athlete under extreme heat conditions, must be considered in the calculation of the new start time. Finally, delaying the start of any of the race-walking and marathon events by more than 2 h, whereas convenient from a pure meteorological point of view is quite irrelevant for the athletes as it may seriously interfere with their preparation, warm-up and nutrition plans.

Women Marathon

Start time (23:59) could be delayed until having more favorable conditions and up to 2:00 a.m. If the solution above cannot be implemented it is recommended to reschedule the women marathon race the same day and time as the men marathon race.

Men Marathon

Start time (23:59) could be delayed until having more favorable conditions and up to 2 a.m.

Women and Men 50 km Race Walks

Start time (23:30) could be delayed until having better thermal conditions and up to 1:15 a.m. (women) and 1:30 (men). The women 50 km Race Walk is likely to be the most difficult to design a contingency plan for, as it is the longest Athletics event in duration. If a delay is impossible, alternate solutions are to organize the race on day 3 after the women 20 km Race Walk (unlikely in the event of a lasting heat wave), or on day 8 after the men 20 km Race Walk, or ultimately to shorten the distance of the event. In any case the start time should not be after 1:30 a.m., if the distance of 50 km is maintained.

Women 20 km Race Walk

Start time (23:30) must be delayed until having more favorable conditions and up to 1:30 a.m.

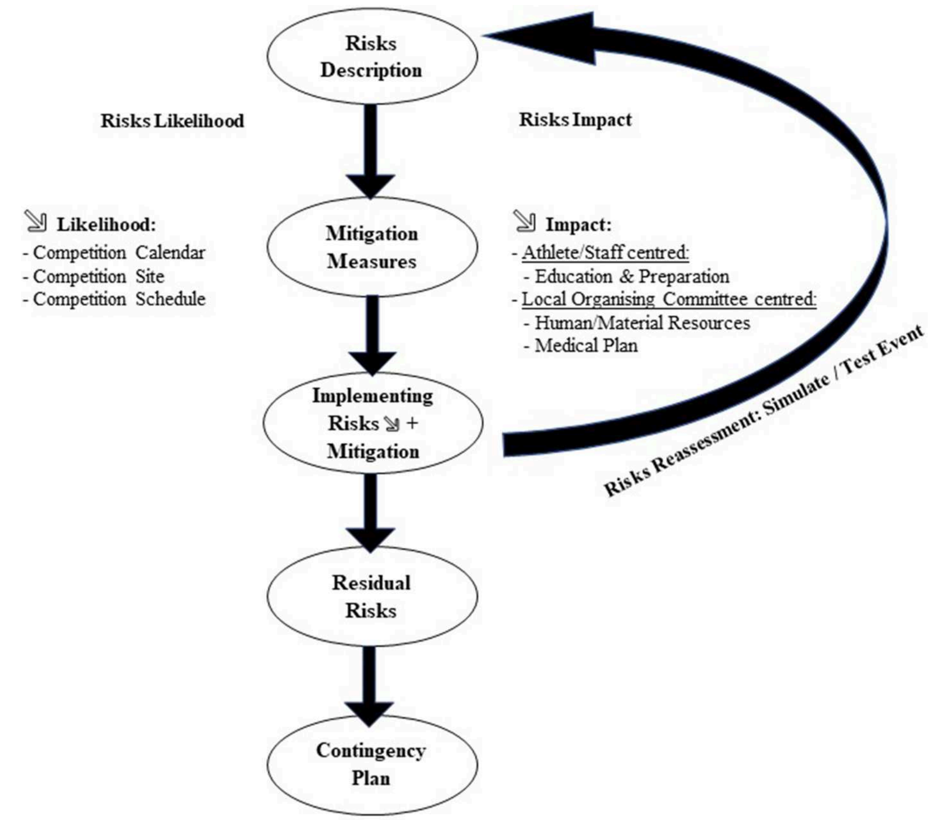

FIGURE 1 | Schematic view of meteorological risks assessment and management prior to Doha 2019 IAAF World Championships.

Men 20 km Race Walk

Start time (23:30) should be delayed until having more favorable conditions and up to 1:30 a.m.

The occurrence of a very unlikely dust storm right before out of stadium endurance events, should be dealt on the same way as the extreme heat risk (see above).

Setting up a Crisis Unit and describing its activation process is an important component of the contingency plan. The Crisis Unit consists of the IAAF and LOC Chief Executive Officer, the IAAF and LOC Medical Delegate, the IAAF Competition, Communication and Broadcasting Departments Directors. Although the IAAF Competition Rules 113[7] gives the IAAF Medical Delegate the power to order one or several athletes to withdraw before, or to immediately retire from an event during, competition, extreme meteorological conditions will trigger the activation of the Crisis Unit. Ideally, this activation should be anticipated as both heat waves and dust storms can be predicted or suspected at least 48 h before their occurrence. Therefore, it is important that a regular prediction and monitoring of these meteorological conditions is organized by the LOC.

[7]IAAF Competition Rules: Available online at: https://www.iaaf.org/about-iaaf/documents/rules-regulations

CONCLUSIONS

Globalization and climate changes accelerated during the last 15 years, increasing the likelihood of sports governing bodies to organize major competitive events in locations where extreme weather conditions may be encountered. Sports policies and regulations may insufficiently or not at all address these extreme meteorological conditions and their potential deleterious consequences on athletes, workforce and spectators' health and safety. Therefore, it is important, while updating or drafting such health policies, to describe and assess all possible weather-related risks (**Figure 1**). This assessment should carefully consider the risks and impact on the competition. Then, specific measures and decisions that could reduce each risk and impacts should be listed and prioritized. The next step should consist on a revision of the climatic risks, after implementing or testing all mitigation measures. This reassessment should be theoretical and if possible, practically done through a test event at a smaller scale. For the risks which remain significant, a contingency plan and a crisis decision-making process should be prepared (**Figure 1**).

AUTHOR CONTRIBUTIONS

SB and PA drafted and reviewed the manuscript, tables, and figure.

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Heat Stress Challenges in Marathon vs. Ultra-Endurance Running

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Several studies have investigated the effect of hot and humid ambient conditions on running exercise up to the marathon. However, studies on exercise longer than marathon are sparse. Events exceeding 6 h can be defined as ultra-endurance and have variable characteristics (e.g., distance, elevation profile, technical difficulty, altitude, night running) making hazardous the transposition of the current knowledge obtained in marathon to ultra-endurance running. Thus, the aim of this manuscript was to discuss the potential differences between marathon and ultra-endurance running in terms of heat stress challenges. The high running intensity (especially for the fastest runners), the urban context with high albedo effect materials, and the hot self-generated microclimate in mass-participation events (especially for the average to slow runners) are specific risk factors associated with marathon running in hot environments. Uphill running/walking (sometimes with poles), exotic destination with long-haul travel, desert environment and the necessity to sustain thermoregulatory and sweating responses for several days are risk factors more specific to ultra-endurance running. These differences call for specific research on the effect of hot ambient conditions in ultra-endurance disciplines to create appropriate recommendations.

Keywords: thermoregulation, ultra-endurance, temperature, hyperthermia, exercise in the heat

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INTRODUCTION

The state of Qatar will host the 17th International Association of Athletics Federations (IAAF) World Championships from the 27th of September to the 6th of October 2019. The track and field events will be held in an air-conditioned stadium, whilst the road events (i.e., marathon and race-walk) will likely be held in hot and humid ambient conditions. World Championships in athletic and other summer sports are often performed in hot conditions. Thus, several studies have considered the effect of such conditions on running event up to the marathon (Cheuvront and Haymes, 2001; Kenefick et al., 2007; Bergeron, 2014). Hot ambient conditions are known to impair performance and increase the risk of heat illness in "classic" endurance events (Maughan, 2010; Racinais et al., 2015). The decrease in performance is linked to the event duration with a larger decrease during marathon than track and field events (Guy et al., 2015). This suggests that the longer the event, the larger the effect of ambient conditions. One could extrapolate that ultra-endurance running would therefore be more affected than marathon running. Ultra-endurance can be defined as an event with a winning time exceeding 6 h (Zaryski and Smith, 2005; da Fonseca-Engelhardt et al., 2013). There has been a marked increase in the number of participants in ultra-endurance running in the past two decades

(Hoffman et al., 2010; da Fonseca-Engelhardt et al., 2013; Cejka et al., 2014; Scheer, 2019), and some events such as the Marathon des Sables, the Western States Endurance Run, the Bad Water Race, or the Grand Raid Reunion are held in extreme hot and humid ambient conditions (temperature >30°C and/or humidity >70%). However, even if ultra-endurance races are longer, exercise intensity may be a more potent determinant of body temperature than exercise duration (Racinais et al., 2019). Thus, ultra-endurance running may have lower thermoregulatory requirements than marathon due to their lower average intensity, albeit those requirements need to be sustained for a longer period of time. In addition, natural environments in ultra-trail running (i.e., ultra-endurance competition running in natural environment with lower than 20% of cemented or asphalted road) are also more diverse between and within events as compared with most city marathons. In summary, the characteristics of ultra-endurance (e.g., distance, elevation profile, technical difficulty, altitude, day, vs. night running) make it difficult to extrapolate the current knowledge obtained in distances shorter than, or equal to, marathon to ultra-endurance (Bergeron, 2014). Therefore, the aim of this manuscript is to explain the need for specific research on the thermoregulatory requirements in ultra-endurance events. This is not a comprehensive review of the existing knowledge on thermoregulatory responses during marathon or other activities, but rather a reflection on the potential specificities of ultra-endurance and their associated research requirements.

METABOLIC HEAT PRODUCTION AND CORE TEMPERATURE

Muscle efficiency in using the energy released by hydrolyzing adenosine triphosphate is about 20–25%, i.e., about 75–80% does not contribute to external work and is internally released as heat (González-Alonso et al., 2000; González-Alonso, 2007; Lim et al., 2008). This metabolic heat production needs to be dissipated to the environment in order to limit the increase in core temperature. Several factors affect the balance between heat production (e.g., exercise intensity) and dissipation (e.g., environmental heat and humidity, skin temperatures, and wetness). During ultra-trail, hill running and the use of trekking poles increase muscle recruitment and impair running economy, consequently resulting in increase heat production for a given running speed (Christensen and Ruhling, 1980; Mora-Rodriguez et al., 2011). Furthermore, the low running pace and the long sections of walking during ultra-endurance running limit self-generated wind velocity and convective cooling when compared with marathon running (Mora-Rodriguez et al., 2011). However, the main factor for heat production is exercise intensity (Racinais et al., 2019) and longer events may be less prone to hyperthermia in a given environment, as they are performed at a lower intensity. For example, a study on 31 heat-acclimated male soldiers participating in a half marathon in tropical environment revealed that 68% of the finishers completed the race with a gastrointestinal temperature > 40°C (Lee et al., 2010), while in a 142 km trail run performed over 6 days in tropical environment, the maximal gastrointestinal temperature was only 38.3–38.7°C (Hue et al., 2014). These findings warrant specific field research during ultra-endurance events in hot and humid ambient conditions to characterize the thermal responses to various race situations. In the meantime, we hypothesize that the moderate intensity during ultra-endurance events for most recreational athletes limits the risk of exertional heat stroke.

PERFORMANCE

Athletic performance can be influenced both positively (sprint) and negatively (middle—long distances) by hot compared with temperate climate. Indeed, whereas an increase in muscle temperature benefits performance during explosive efforts, an increase in core temperature may impair performance during prolonged exercise in hot and/or humid environments by challenging the circulatory system. Briefly, the narrowing of the core-to-skin temperature gradient lead to a redistribution of the blood flow toward the skin for heat dissipation, and the subsequent decrease in ventricular filling pressure reducing stroke volume is exacerbated by an intrinsic increase in heart rate. Moreover, the necessity to sustain an elevated sweat rate for heat dissipation may lead to dehydration if fluids are not replaced. Thus, during the IAAF world championships held with an ambient temperature above 25°C, an ∼2% decrease in performance was reported for distances longer than 5,000 m as compared to the other editions, this difference being as much as 3% in marathon for male athletes (Guy et al., 2015). The decrement in marathon performance exists for both men and women of various performance levels although the slowest runners are more affected by the heat than their faster counterparts (Ely et al., 2007, 2008; Vihma, 2010). In ultra-endurance, a decrease in performance of ∼8% has been reported in participants competing in the Western States Endurance Run (161 km and 6,000 m of cumulative climb) during a hot edition (2006, temperature ranging from 7.2 to 38.0°C), compared with a cooler edition (2007, temperature ranging from 2.2 to 30.6°C) (Parise and Hoffman, 2011). Conversely to marathon, the performance of the slowest ultra-runners was less impacted by hot conditions compared with the fastest ones (Parise and Hoffman, 2011). This was partially explained by the fact that slower runners ran more overnight, at a time of lower heat stress, than their faster counterparts in this ultra-endurance races starting early in the morning. Slow ultra-runners may also have less technical abilities, limiting their ability to run fast, and thus produce heat on an uneven terrain. An explanation for the greater performance changes in the heat for slow marathon runners could be the hot microclimate generated by large groups of runners close to each other during mass participation events (De Freitas et al., 1985). In this condition, radiant and convective heat losses are limited within the group, resulting in excessive heat load during the race, directly affecting performance. Although ultra-endurance is expanding rapidly, it is not as popular compared with the largest marathon in terms of number of participants (e.g., 49,155 runners in Paris marathon in 2019 vs. 2,300 runners in the Ultra-Trail du Mont-Blanc).

Thus, in ultra-trail, except at the start, the crowd is traditionally less dense and spread over a longer distance, with most of the race performed in a single file on narrow pathways. This likely limits the hot microclimate generated by large groups as observed in marathons.

ENVIRONMENT AND CHARACTERISTICS OF RACES

The most famous and popular marathons are held in western city environment (Boston, Chicago, London, New York, Paris). The shade from the built environment (building and trees) produces low sky view factors over roads and protects the runners from the direct radiant and diffuse radiation heat (Kenny et al., 2008; Lai et al., 2017). Inversely, the usage of high albedo-materials (asphalt road, glass panes…) could impact the urban heat island in street canyons and increase overall thermal stress (Erell et al., 2014; Middel et al., 2014). The lower wind velocity in cities due to the surrounding buildings and constructions also impairs heat dissipation (**Figure 1**).

Conversely, ultra-endurance races (particularly ultra-trail running) traditionally take place in natural environments (mountain, desert, forest…) with large positive and negative elevation. The regulation of trail running states that road sections should not exceed 20% of the total course (ITRA, 2019). The diversity of natural environments in ultra-trail running makes the study to heat and radiation exposure more difficult. For example, sky view factor, and direct radiation can be completely absent when running in a forest vs. maximum in deserts such as the multistage ultramarathon event called the "marathon des sables." Weather conditions vary as much as the course topography and can change considerably from start to finish for a given race (night and day running, altitude, temperature, precipitations…). As mentioned above, temperatures ranged from 7.2 to 38.0°C in the 2006 Western States Endurance Run (Parise and Hoffman, 2011). The Grand Raid de la Reunion is a race starting and finishing at sea level with temperatures and relative humidity often exceeding 30°C and 80%, respectively; while other sections are ran at an altitude above 2,000 m where temperatures can be negative (Association GRR, 2019; Lai-Cheung-Kit et al., 2019). These variations may be viewed as a physiological constraint, but the low temperatures at altitude and during the nights may also minimize the level of heat stress during ultra-endurance races as compared with the marathon (Bongers et al., 2015; Tyler et al., 2015; **Figure 2**).

In addition, ultra-endurance events are commonly held in exotic destinations, with ultra-endurance runners being more motivated by nature and life experience than the competition itself (Doppelmayr and Molkenthin, 2004; Waśkiewicz et al., 2018). Such destinations may necessitate to long-haul flight and jet lag, with amateur participants arriving only a few days before the race. This often prevents enough recovery and acclimatization to the local conditions. Ideally, the heat acclimatization period should last 2 weeks in order to maximize adaptations (i.e., decreases in heart rate, skin and rectal temperature, increases in sweat rate, and work capacity) and limit the impact of exercising in a warm environment (Périard et al., 2015; Racinais et al., 2015). Furthermore, long-haul flights can induce mild dehydration from insufficient fluid intake, consumption of diuretic beverages, and low ambient humidity (Hamada et al., 2002) despite the recommendation to ensure euhydration before exercising in hot environments (Racinais et al., 2015).

CLOTHING

Clothing substantially differs between the two disciplines. Marathon runners traditionally wear minimalist and light textiles: shorts, t-shirts, or tank tops. Trail runners traditionally wear a more complex outfit including shorts with underneath compression shorts (to limit irritation due to long distance), compression stockings, a hydration pack, and a headscarf or a cap. It is also often necessary/mandatory in ultra-endurance races to carry warm clothing, gloves and a raincoat to anticipate changes in environmental conditions. This increases total weight and thus thermal stress in the warmest sections of the race. Clothing creates a microenvironment between the skin and clothing (Bishop et al., 2000). Clothing can act as a protective function by reducing radiant heat gain and thermal stress (Gavin, 2003). Exercise in the shade as opposed to in the sun reduces radiant heat gain as much as 100 W and decreases the need for evaporative heat loss (Nielsen et al., 1988; Gavin, 2003). In this context semi-nude (short, socks, and shoes) exercise during marathon is a disadvantage compared with ultra-endurance considering radiant heat load. On the other hand, clothing and gear represents a layer of insulation and act to inhibit evaporative and convective cooling, and could significantly minimize thermoregulatory capacities of ultra-endurance runners (Davis and Bishop, 2013; Davis et al., 2017). Indeed, the evaporation of sweat from the skin surface is the main modifiable avenue of heat lost (Périard and Racinais, 2015). Then, the insulative effect of clothing represents a significant restriction on heat dissipation compared to the protective function against radiant heat gain. Finally, color of clothing can affect radiative heat gain, where white clothing reduces it compared with black clothing (Shkolnik et al., 1980; Nielsen, 1990), but no clothing color habits are specific to a discipline to our knowledge.

HYDRATION REQUIREMENT AND DEHYDRATION

Sufficient hydration prior to, during, and after the race is crucial for athletic performance and safety during training and competition in the heat (Bergeron et al., 2012; Racinais et al., 2015). Athletes should avoid body water deficits exceeding 2% of their body mass during exercise in order to prevent an impairment of thermoregulatory function, an elevation of cardiovascular strain and an impairment of aerobic exercise performance in many conditions (e.g., warmer, longer, more intense) (Valentino et al., 2015; Kenefick, 2018). However, in a 161-km ultra-marathon, it has been established that runners tend to lose between 2 and 4% without core temperature

FIGURE 1 | Heat stress challenges in marathon runners (adapted with permission from http://www.ephysiol.com/).

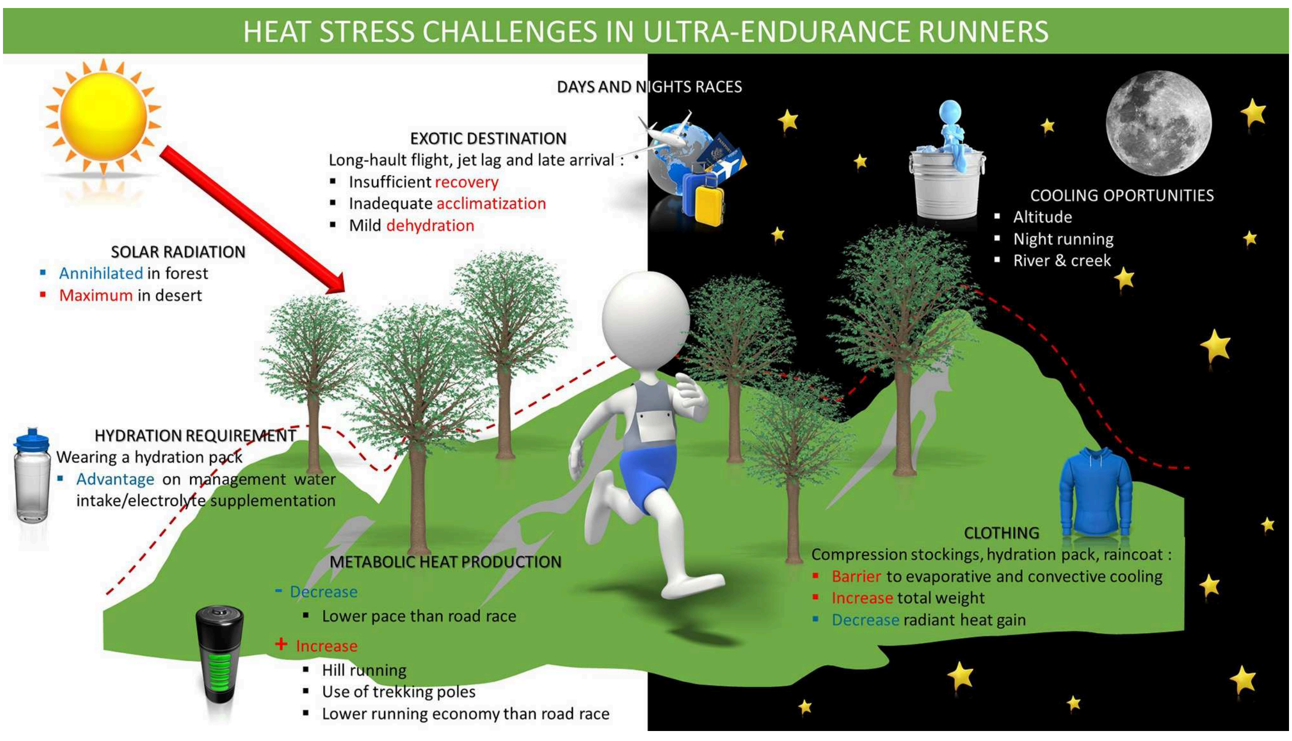

FIGURE 2 | Heat stress challenges in ultra-endurance runners (adapted with permission from http://www.ephysiol.com/).

elevation or consequences on performance (Lebus et al., 2010; Hoffman and Stuempfle, 2014; Valentino et al., 2015). A review of fluid balance data from marathon running literature provides average dehydration values of 3.2% in cool weather to 4% in warm weather (Cheuvront and Haymes, 2001). Actually the level of sustainable dehydration and hydration guidelines during endurance are a much-debated topics (Wall et al., 2015; Kenefick, 2018). Any ways, ultra-endurance athletes adopt hydration and sodium supplementation strategies, just as endurance athletes do for fluid replacement management. Nevertheless, several differences can exist between ultra-endurance and marathon and the long duration of the ultra-endurance events may create sport-specific hydration issues:

Firstly, while marathon runners have only opportunity to rehydrate at drink stations, ultra-endurance athletes have regular access to fluids by wearing a hydration pack or belt. In ultra-endurance, carrying your gear may help with regular hydration but also impair evaporation and convective cooling.

Secondly, gastro-intestinal (GI) distress may impair athlete ability to feed and hydrate adequately in both disciplines. The prevalence of GI symptoms ranges from 4 to 52% among marathon runners (Rehrer et al., 1989; Halvorsen et al., 1990; Costa et al., 2017; Pugh et al., 2018), but reaches 35–96% among ultra-runners (Stuempfle and Hoffman, 2015; Wardenaar et al., 2015; Stuempfle et al., 2016). These GIs symptoms, and particularly nausea and vomiting if the fluid losses are not compensated, could lead to and worsen progressive dehydration and impair thermoregulation. The reduction of blood flow and then whole-body sweat rate decrease heat loss, thus accounting for the increase in core temperature (American College of Sports Medicine et al., 2007).

Finally, in conjunction with hydration level and sodium supplementation; the occurrence and incidence of Exercise Associated Hyponatremia (EAH) varies with exercise type and duration, as well as the level of heat stress during the event (Hew-Butler et al., 2015). The incidence of EAH has been largely investigated in marathoners, ranging from 0 to 12–13% of races finishers and even under cool conditions (Reid et al., 2004; Almond et al., 2005; Mettler et al., 2008; Kipps et al., 2011). In ultra-endurance incidence is highly variable between studies and ranges between 5 and 51% of runners (Lebus et al., 2010; Hoffman et al., 2012, 2013; Cairns and Hew-Butler, 2015). These important variations in EAH prevalence between studies could be due to several factors such as exercise intensity or duration, hydration strategies (overhydration), salt supplementation, and environmental temperature and hygrometry (Knechtle and Nikolaidis, 2018).

PERSPECTIVES

The purpose of this manuscript was to present some potential differences between marathon and ultra-endurance running in terms of heat stress challenges. The high running intensity (especially for the fastest runners), the urban context with high albedo effect materials, and the hot self-generated microclimate in mass-participation events (especially for the average to slow runners) are the main specific risk factors for high heat load associated with marathon running in hot environments. Uphill running/walking (sometimes with poles), lower self-generated wind velocity, exotic destination with long-haul travel, desert environment and the necessity to sustain a thermoregulatory and sweating responses for days represent some of the risk factors more specific to ultra-endurance. Based on these differences, it appears difficult to extrapolate our knowledge from traditional marathon to ultra-endurance events, and specific research appeared to be warranted. Future research should notably determine the thermoregulatory responses to ultra-endurance events lasting for a day or more and the effect of changing of environment within the same events. It is also important to determine the hydration requirements in such conditions along the associated risk for dehydration, gastrointestinal problems, and hyponatremia. Lastly, the impact of clothing and gear (e.g., back-pack, lights, and other mandatory equipment for ultra-endurance event) on thermoregulation should also be considered.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Effect of a 16-Day Altitude Training Camp on 3,000-m Steeplechase Running Energetics and Biomechanics: A Case Study

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The purpose of this study was to investigate the effect of a 16-day training camp at moderate altitude on running energetics and biomechanics in an elite female 3,000-m steeplechase athlete (personal best: 9 min 36.15 s). The 16-day intervention included living and training at 1,600 m altitude. A maximal incremental test was performed at sea level to determine the maximal oxygen uptake ($\dot{V}O_2$ max). Before (pre-) and after (post-) intervention, the participant performed a specific training session consisting of 10 × 400 m with 5 hurdles with oxygen uptake ($\dot{V}O_2$), blood lactate, stride length and stride rate being measured. A video analysis determined take-off distance and landing around the hurdle (DT_H and DL_H), take-off velocity and landing around the hurdle (VT_H and VL_H), and the maximal height over the hurdle (M_H). The results demonstrated that the mean $\dot{V}O_2$ maintained during the ten 400 m trials represented 84–86% of $\dot{V}O_2$ max and did not change from pre- to post-intervention ($p = 0.22$). Mean blood lactate measured on the 6 last 400-m efforts increased significantly (12.0 ± 2.2 vs. 17.0 ± 1.6 mmol.l^{-1}; $p < 0.05$). On the other hand, post-intervention maximal lactate decreased from 20.1 to 16.0 mmol.l^{-1}. Biomechanical analysis revealed that running velocity increased from 5.12 ± 0.16 to 5.49 ± 0.19 m.s^{-1} ($p < 0.001$), concomitantly with stride length (1.63 ± 0.05 vs. 1.73 ± 0.06 m; $p < 0.001$). However, stride rate did not change (3.15 ± 0.03 vs. 3.16 ± 0.02 Hz; $p = 0.14$). While DT_H was not significantly different from pre- to post- (1.34 ± 0.08 vs. 1.40 ± 0.07 m; $p = 0.09$), DL_H was significantly longer (1.17 ± 0.07 vs. 1.36 ± 0.05 m; $p < 0.01$). VT_H and VL_H significantly improved after intervention (5.00 ± 0.14 vs. 5.33 ± 0.16 m.s^{-}1 and 5.18 ± 0.13 vs. 5.51 ± 0.22 m.s^{-1}, respectively; both $p < 0.01$). Finally, M_H increased from pre- to post- (52.5 ± 3.8 vs. 54.9 ± 2.1 cm; $p < 0.05$). A 16-day moderate altitude training camp allowed an elite female 3,000-m steeplechase athlete to improve running velocity through a greater glycolytic—but not aerobic—metabolism.

Keywords: hurdle, metabolism, kinetics, kinematics, hypoxia, women

INTRODUCTION

The analysis of the actual male and female 3,000-m steeplechase world records demonstrates that this specific race is ran 3–4% slower than a classical 3,000-m race. This difference in running velocity corresponds to a decrease of ∼3% of the oxygen uptake ($\dot{V}O_2$) (Earl et al., 2015). This suggests that 3,000-m steeplechase's pace is near 95% of the athlete's maximal oxygen uptake ($\dot{V}O_2$ max). Thus the ability to elicit a high level of $\dot{V}O_2$ max during the race is key within the steeplechase performance. However, most of the steeplechase-related studies have focused mainly on the biomechanics of hurdling and water jumps (Hunter and Bushnell, 2006; Hunter et al., 2008; Kipp et al., 2017). Three thousand meter steeplechase athletes compete around the track and have to clear 28 hurdles and seven water jumps over the 3,000-m distance. Therefore, the discipline's performance might depend on technical abilities. Generally, the biomechanical parameters studied are take-off (DT_H) and landing distances (DL_H) from the hurdle, time to clear the hurdle (T_H), take-off velocity (VT_H) and landing velocity around the hurdle (VL_H), maximal height over the hurdle (M_H), stride rate (SR), and stride length (SL), knee and hip angles and/or ground reaction forces (Hunter and Bushnell, 2006; Hunter et al., 2008; Chortiatinos et al., 2010; Hanley and Bissas, 2017; Kipp et al., 2017). A major element to succeed in hurdling events is the athlete's ability to maintain horizontal velocity when they clear the hurdle (Hunter et al., 2008). However, the recent work of Kipp et al. (2017) demonstrated that take-off induces a decrease of the horizontal velocity. This reduction is not compensated after the hurdle, because the horizontal positive impulse increases at landing. In other words, the runner must increase take-off distance in order to clear the barrier as close as possible to the hedge and limit the loss of velocity induced by clearing the hurdle (Hunter et al., 2008). From a kinetic and kinematic point of view, the runner must accelerate before the hurdle in order to increase the vertical forces at take-off and decrease angle at take-off (Salo et al., 1997; Chortiatinos et al., 2010; Kipp et al., 2017). In order to clear a hurdle, a greater muscle activation and force development is needed (Kipp et al., 2017). Therefore, a 3,000-m steeplechase athlete, having 35 hurdles to clear throughout the race needs more force production and probably more anaerobic capacities in comparison to a 3,000-m athlete.

To improve both aerobic and anaerobic capacities in highly-trained endurance runners, living and training at moderate altitude (e.g., 1,600–2,200 m) has been suggested (Gore et al., 2007; Chapman et al., 2014). Recommended procedure to train in altitude were first to decrease the absolute running speed to facilitate the acclimatization process and to have at least 4 weeks of altitude residence (Chapman et al., 2014). Training at $\dot{V}O_2$ max or anaerobic threshold at moderate altitude (1,400 and 2,100 m) enhances the use of the anaerobic metabolism (Sharma et al., 2019). Indeed, the greater level of muscle deoxygenation induced by hypoxia improved muscle pH regulation, buffer capacity, and anaerobic glycolytic activity (Gore et al., 2007; Sharma et al., 2019). Such adaptations may be particularly effective for 3,000-m steeplechase athletes since both aerobic and anaerobic contributions are required.

The purpose of this study was therefore to test the effectiveness of a 16-day training camp at moderate altitude (1,600 m) on energetics and biomechanics parameters in an elite female 3,000-m steeplechase athlete. We hypothesized that such intervention would improve performance by increasing both aerobic and anaerobic contributions. The increased anaerobic contribution may result in improved hurdling technical ability.

MATERIALS AND METHODS

One elite female 3,000-m steeplechase athlete (age: 24 years; height: 172 cm; body mass: 58 kg, personal best: 9 min 36.15 s) gave her informed consent to participate in this study.

Energetic Parameters

Before intervention, the participant was asked to perform a maximal incremental test (2-min stage) at sea level in order to determine $\dot{V}O_2$ max and velocity that elicited $\dot{V}O_2$ max ($v\dot{V}O_2$ max). Before (pre-) and after (post-) intervention, the participant also performed a specific training session consisting of 10 × 400 m with 5 hurdles and a half time effort of passive recovery between each 400-m effort (e.g., a 74 s 400-m run in this case will equal 37 s of passive recovery). This specific training session took place the morning of the day the athlete left sea level and 8 days after her return to sea level. Each 400 m was run at the target velocity of the future 3,000-m steeplechase race pace (5.2 m.s^{-1}). During this training session, $\dot{V}O_2$ (in ml.kg^{-1}.min^{-1}) was continuously measured using a portable unit system (K5, Cosmed Roma, Italy) and calculated as the average $\dot{V}O_2$ of the last 20-s period for each 400 m. This $\dot{V}O_2$ was expressed as a percentage of $\dot{V}O_2$ max. Immediately after the 5th, 6th, 7th, 8th, and 9th 400-m effort, blood lactate was measured using a Lactate Pro 2 (Arkray, LT-1730, Kyoto, Japan). For the last 400 m (10th repetition), blood lactate was measured 2 min after exercise cessation.

Mechanical Parameters

For each 400-m effort, contact time (T_c), flight time (T_f), SR, and SL were determined through a 20-m long subsection of the 400 m, using an iPhone SE (240 Hz, Apple, Cupertino, CA, USA) positioned 30 m before the 3rd hurdle. Finally, a fixed video camera (50 Hz, Canon Legria, Paris, France) was placed perpendicularly to the third hurdle in order to determine DT_H, DL_H, M_H, T_H, VT_H, and VL_H (**Figure 1**). VT_H and VL_H were calculated as the average velocity of the step just before take-off and just after landing. All video analysis was realized with Kinovea software (v 0.8.15).

Moderate Altitude Camp

The participant was then asked to attend a 16-day moderate altitude training camp where she had to live and train at the same altitude (1,600 m). Two daily sessions were implemented throughout the 16-day intervention and were composed of 47% of low-intensity aerobic training (<90% of $v\dot{V}O_2$ max), 9.4% of high-intensity aerobic training (interval training, within 90–110% of $v\dot{V}O_2$ max), 9.4% of very high-intensity lactic training (>110% of $v\dot{V}O_2$ max), 9.4% of resistance training, and 25% of

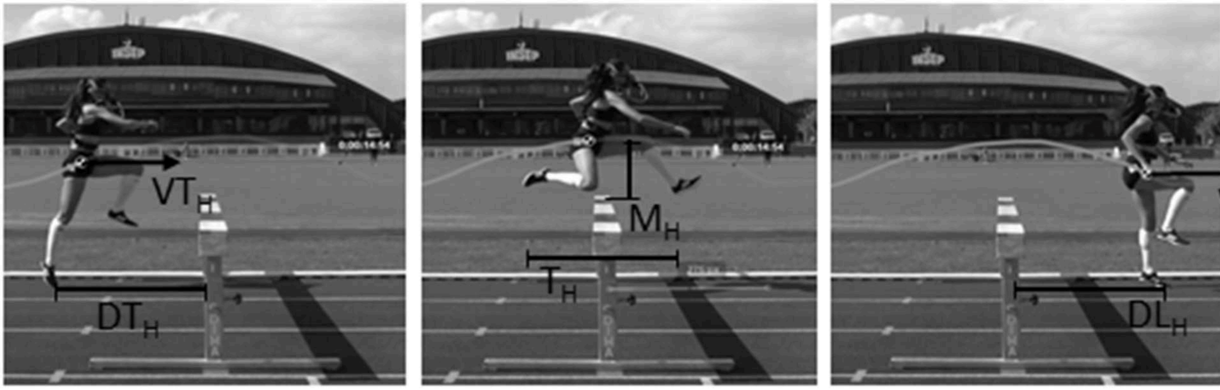

FIGURE 1 | Mechanical parameters recorded during the hurdle clearing. Take-off (DT_H) and landing distances (DL_H) around the hurdle, maximal height over the hurdle (M_H), time to clear the hurdle (T_H) and take-off (VT_H) and landing velocities (VL_H) around the hurdle.

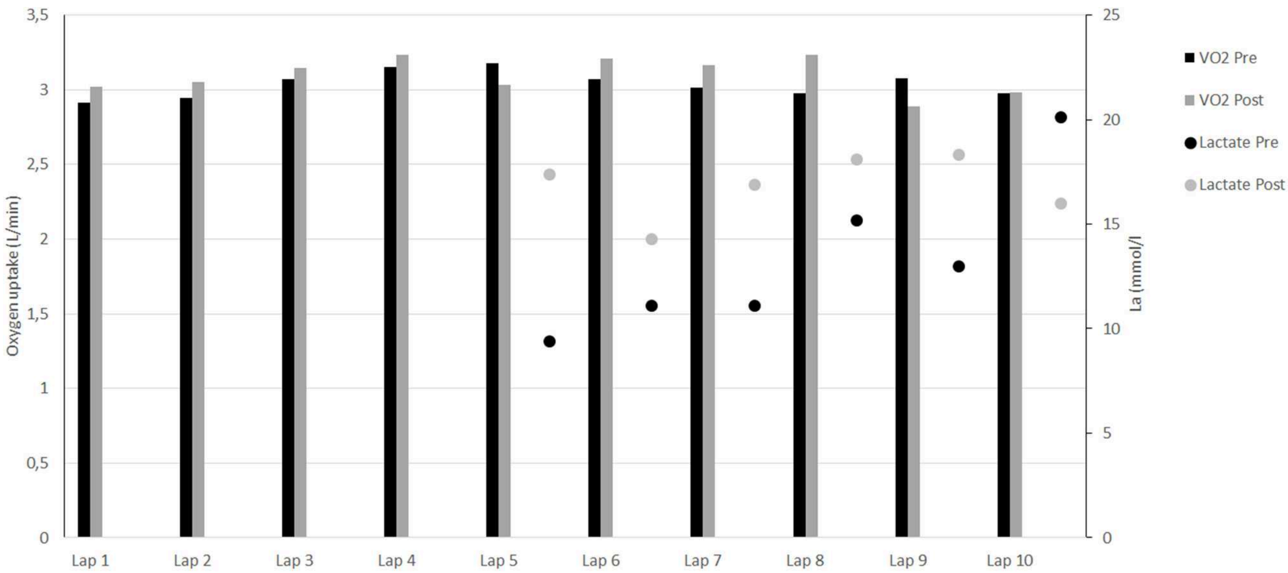

FIGURE 2 | Evolution of oxygen uptake and blood lactate during the 10 × 400-m.

recovery where the athlete had either physiotherapy massage or free time.

Statistics

In order to compare pre- and post- intervention variables measured during the 10 × 400 m, a parametric student t-test for repeated measures was performed. The level of significance was set at $p \leq 0.05$.

RESULTS

Energetics Parameters

Before intervention, participant's $\dot{V}O_2$ max and $v\dot{V}O_2$ max were, respectively 62.1 ml.min^{-1}.kg^{-1} and 20.0 km.h^{-1}. The mean $\dot{V}O_2$ measured during the ten 400-m efforts did not change from pre- to post- ($p = 0.22$; **Figure 2**). This represented 84.3 ± 2.4% and 86.0 ± 3.3% of $\dot{V}O_2max$ for pre- and post-, respectively. The velocity maintained during the 10 × 400 m represented 93.1 ± 0.7% of $v\dot{V}O_2max$ before intervention and increased significantly to 95.4 ± 1.1% of $v\dot{V}O_2$ max after intervention ($p < 0.001$). Mean blood lactate measurements from the 5th to the 9th 400-m efforts increased significantly (12.0 ± 2.2 vs. 17.0 ± 1.6 mmol.l^{-1}; $p < 0.05$; **Figure 2**), unlike blood lactate measurements after the 10th 400-m repetition (2 min after exercise cessation) which decreased from 20.1 to 16.0 mmol.l^{-1} following the intervention (**Figure 2**).

Mechanical Parameters

Biomechanical analysis revealed that running velocity increased from 5.12 ± 0.16 to 5.49 ± 0.19 m.s^{-1} ($p \leq 0.001$), concomitantly with SL (1.63 ± 0.05 vs. 1.73 ± 0.06 m; $p < 0.001$). However, SR did not change from pre- to post- (3.15 ± 0.03 vs. 3.16 ± 0.02 Hz; $p = 0.14$). **Table 1** presents the evolution of DT_H, DL_H M_H, T_H, $VL_{H,}$ and VT_H from pre- to post-intervention.

DISCUSSION

The present study suggests that a 16-day training camp including living and training at moderate altitude (1,600 m) induces a gain in the physiological and biomechanical parameters of a 3,000-m steeplechase specific training session ran by an elite female athlete. Such gains appear to be associated with energetic adaptations—mainly through a higher glycolytic, but not aerobic, metabolism—as well as modifications regarding the biomechanical parameters (i.e., SL, VT_H, and VL_H).

The specific training session of 10 × 400 m with hurdles at race pace did not allow the athlete to reach $\dot{V}O_2$ max. Indeed, the average $\dot{V}O_2$ was ∼85% of $\dot{V}O_2$ max, although the 400 m was run at 95% of v$\dot{V}O_2$ max. This seems logical since the passive recovery allowed between each 400 m effort prevented the athlete to reach $\dot{V}O_2$ max during such specific session. The inclusion of hurdles generally results in an increase of the hurdle's approach velocity (Earl et al., 2015) as well as a decrease of the average running velocity (3,000-m steeplechase is 30 s slower compared to a classical 3,000 m; Chortiatinos et al., 2010). Therefore, increase in $\dot{V}O_2$ between 3,000-m steeplechase and classical 3,000-m is small and non-significant (Earl et al., 2015). Thus, the decrease of running velocity during a 3,000 m steeplechase may compensate a part of the increase in the energetic demand requested for hurdling technique. This discipline requires to clear 35 hurdles, therefore, the anaerobic capacity might be more solicited than during a classical 3,000-m race (Kipp et al., 2017). The 16-day training camp at moderate altitude training might have an impact on this anaerobic capacity.

The general consensus about living and training at altitude method is that altitude chronic exposure (residence) and increased relative intensity of training induced by hypoxic training result in physiological and performance improvements (Saunders et al., 2009; Pugliese et al., 2014; Solli et al., 2017). According to the meta-analysis from Bonetti and Hopkins (2009), the velocity maintained during the 10 × 400-m increased by 2.4%, meanwhile the intervention did not induce any change in $\dot{V}O_2$. This result appears in line with previous studies, suggesting that training at moderate altitude during a relatively short period (16 days) does not lead to $\dot{V}O_2$ max development (Levine and Stray-Gundersen, 1997; Bailey et al., 1998; Gough et al., 2012). Beside potential factors (e.g., iron status, reduction in training qualities despite higher relative intensity) influencing the effects of living and training at altitude, various underlying mechanisms have been suggested (Levine and Stray-Gundersen, 2005). Based on this, it is tempting to associate the improved running velocity with a greater glycolytic metabolism where blood lactate measured after each 400-m effort increased over time and decreased after exercise cessation (2 min of passive recovery). Therefore, contrarily to the physiological adaptations (an increase in $\dot{V}O_2$ max and no variation in the glycolytic pathway) generally expected at sea level for low aerobic intensity and interval training at v$\dot{V}O_2$ max (Billat, 2001; MacInnis and Gibala, 2017), the increased running intensity for the same level of $\dot{V}O_2$ induced by the lower oxygen availability at moderate altitude might have participated in an increased anaerobic contribution at the anaerobic threshold and maximal aerobic intensities (Gore et al., 2007; Sharma et al., 2019). The training performed by the present elite female steeplechase runner could have impacted her glycolytic metabolism and improved her capacity to produce more lactate when exercising, as well as a greater buffer capacity during the recovery periods. These specific adaptations observed for the present athlete studied, might be in line with the running intensities sustained during training. Indeed, during altitude training, reduction in absolute altitude training intensity is essential and a meticulous control of training load is key (Mujika et al., 2019). However, some athletes are more affected than others by the lower barometric pressure and oxygen availability at altitude. At 2,100 m altitude, running speed is impaired from 6% to more than 10% for elite athlete (Sharma et al., 2019). Thus, the present athlete studied might have not reduced enough of her running velocity during the altitude camp, inducing more glycolytic adaptations.

From a biomechanical point of view, these results demonstrated that living and training at moderate altitude improved the running velocity and SL. According to Slawinski et al. (2001), within 0–7 m.s^{-1}, an increase of the running velocity is mainly associated with an increase in SL. In reference to pre-values, DT_H remains constant after intervention. However, the athlete arrives in front of the hurdle with greater VT_H, resulting in a higher M_H. To properly clear the hurdle, the athlete must increase M_H and DT_H. Indeed, better hurdlers present a greater take-off distance and a lower take-off angle (Salo et al., 1997). We can therefore speculate that altitude training did not induce any technical adaptations as it was previously demonstrated (Stickford et al., 2017). However, the use of only one athlete without control group clearly limits the interpretation of the present results. Two weeks training period, which offer a potential pathway for further 3,000 m steeplechase performance improvements in highly trained runner. It is more difficult to attribute, with certitude, the observed improvement to the combined effect of training and exposure to hypoxia.

In summary, 2 weeks of training allowed an elite female 3,000-m steeplechase athlete to improve running velocity through a greater glycolytic—but not aerobic—metabolism. However, despite some biomechanical adjustments, specific technical training seems to be necessary in order to improve hurdling technical ability for this specific athlete. These physiological adaptations may be attributed to the benefit of combined training and exposure to hypoxia.

TABLE 1 | Take-off and landing distances around the hurdle (DT_H and DL_H), maximal height over the hurdle (M_H), time to clear the hurdle (T_H) and take-off (VT_H) and landing velocities (VL_H) around the hurdle.

	Pre-	Post-
VT_H (m.s^{-1})	5.00 ± 0.14	5.33 ± 0.16**
DT_H (m)	1.34 ± 0.08	1.41 ± 0.07
M_H (cm)	52.5 ± 3.8	54.9 ± 2.1*
T_H (s)	0.45 ± 0.05	0.46 ± 0.03
VL_H (m.s^{-1})	5.18 ± 0.13	5.51 ± 0.22**
DL_H (m)	1.17 ± 0.07	1.36 ± 0.05**

These data were averaged for the 10 laps ($p < 0.05$; **$p < 0.01$).*

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The participant provided her written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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