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Debates in elite sports and performance enhancement 2022

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Debates in elite sports and performance enhancement: 2022

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Editorial: Debates in elite sports and performance enhancement: 2022

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Editorial on the Research Topic
Debates in elite sports and performance enhancement: 2022

1. Introduction

Success in sport depends on research and the advancement of applied science to ensure health and achieve performance enhancement among athletes. However, to further progress evidence-based practices, there is a need to critically revise and discuss around emerging challenges that sport practitioners face. Frontiers in Sport and Active Living recognizes the importance of facilitating debate and discussion amongst the community, and so has organized this Research Topic, offering a platform for such discussion to occur in the field of sports science. This Research Topic entitled "Debates in Elite Sports and Performance Enhancement" aimed to highlight themes that foster debate and discussion in the high-performance sports industry. We encouraged authors to submit opinions or perspective pieces that focus on the "pros" or "cons" of all areas surrounding the athlete's environment for performance enhancement. Our final goal was to respectfully challenge perspectives and paradigms to enhance sports performance.

2. Articles

This Research Topic of Frontiers in Sports and Active Living, "Debates in Elite Sports and Performance Enhancement, 2022" contains 10 original manuscripts meeting the editorial criteria, including one original research article (McCaskie et al.), three opinion piece articles (Beato, Desroches and Goulet, Lerebourg and Coquart), one review (Flack et al.), one systematic review (Gualtieri et al.), two brief research reports (Beato et al., Beato et al.), and two perspective articles (Baker et al. Johnston et al.).

McCaskie et al. studied the relationship between pre-season body composition, in-season match performance, and match availability in female players competing in the Australian Football League Women's competition. This study found that body composition characteristics are not able to differentiate higher versus lower performing players.

In an opinion article, Beato provided recommendations in the field of research design, specifically, randomized controlled trials and data interpretation. The author aimed at improving the robustness of future strength and conditioning research (e.g., training, performance, injury prevention) and avoiding the replication of common mistakes such as the use of inadequate sample sizes, type 1 and type 2 errors, incorrect interpretation of confidence intervals, the use of magnitude-based inference, and the use of within-group comparisons instead of between-group comparisons to determine longitudinal differences between intervention.

In their opinion article, Desroches and Goulet elaborated on the challenges and future directions of the Ironman™ triathlon, an ultra-endurance event consisting in 3.8 km swimming, 180 km cycling and 42.2 km running. In particular, by the means of predictive analyses, they elucidated whether an Ironman™ distance triathlon under 7-h might be achievable in 2022 without external assistance and with the current swimming, cycling, and running equipment. Moreover, they discussed how external aid should be deployed to achieve the breaking of the 7-h mark.

In their opinion article, Lerebourg and Coquart critically analyzed the "ideal" running pattern to optimize running performance, while taking into consideration the multifactorial aspects of performance (i.e., physiological, biomechanical, psychological, environmental, and technological factors). In view of the multifactorial nature of performance, they encouraged turning to Big Data and Artificial Intelligence approaches to facilitate the programming components (i.e., planning, implementing, monitoring, predicting) of sports performance.

Flack et al. reviewed articles describing the possible interaction between bilirubin and exercise and the expected effects on metabolic health and athletic performance by describing the underlying mechanisms at hormonal and cardiovascular level.

The systematic review of Gualtieri et al. provided a comprehensive summary of the evidence about absolute and individual velocity thresholds used to classify high-speed running and sprinting demands in soccer, competitive standards, and lastly, strategies for eliciting high-speed running and sprinting during training in professional adult soccer players.

In their brief research report, Beato et al. compared the external and internal training load demands of sided-game drills in professional soccer players during the official season. While sided-games can replicate or even exceed some match-specific intensity parameters, high-speed running and sprinting distances were consistently lower compared to official matches. These findings can inform practical applications for soccer practitioners.

In another brief research report, Beato et al. compared internal and external loads between different between sided game formats, and assessed whether positional differences exist in professional soccer players. Overall, different formats may be used to induce selective responses (e.g., accelerations, rate of perceived exertion), with playing position influencing external load metrics, such as high-speed running and decelerations but not rate of perceived exertion and distance.

Baker et al. in their perspective article, highlighted several discrepancies in the way development is conceptualized, contextualized, and operationalized between different competitive levels (e.g., pre-professional sport and professional sport). They used available evidence to provide guidance for researchers and practitioners to encourage the delivery of structured developmental programming in professional sport systems to aid with the transitionary period between pre-elite and elite levels, and to help foster career longevity.

In their perspective article, Johnston et al. warranted the need for researchers and practitioners to consider the clarity and consistency of their language in the context of athlete development. This article reported evidence of incongruency in the way terms and expressions are defined, understood, and operationalized. The authors highlighted potentially blurry terms and drew attention to potential avenues for future research.

3. Final considerations

This research topic aims to facilitate the debate and discussion amongst the sport science community. The ten articles included in this Research Topic "Debates in Elite Sports and Performance Enhancement, 2022" respectfully challenged perspectives and paradigms to enhance sports performance. We believe that the findings and considerations reported in these articles can contribute to the improvement of practitioners' practice and will foster new research questions.

Author contributions

MB, JM, AD have equally collaborated to the writing of this editorial. All authors contributed to the article and approved the submitted version.

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.

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Is a sub 7-h Ironman™ possible?

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Introduction

An Ironman™ (IM) triathlon is an ultra-endurance event consisting in swimming 3.8, cycling 180 and running 42.2 km. The first ever IM triathlon was held in Hawaii in 1978 and won in a time of 11 h 46 min and 58 sec (Millet et al., 2007; Lepers, 2008). Since then, and especially more so following the first IM event in the continental United States held in Lake Placid in 1999, the IM distance triathlon has grown exponentially in popularity and the best finishing time is significantly faster. To this effect, the men's world record is currently held by the 2008 Olympic champion, Jan Frodeno, who completed the distance in a time of 7 h 27 min and 53 sec, which was achieved in 2021 in Germany in an event specifically designed to break the world record called the *Zwift Tri Battle Royale* (ZTBR). This record was broken on the same year by the 2021 Olympic champion Kristian Blummenfelt in a time of 7 h 21 min and 12 sec at IM Cozumel, but the swim was current-assisted, so it may be argued that this time should not be considered as the world record.[1] On the other hand, the women's world record is held by Chrissie Wellington; she completed the distance in 8 h 18 min and 13 sec.

Just as people wondered if it would be possible to break the 4 min barrier for the mile (Denison, 2006) or the 2-h barrier for the marathon (Joyner et al., 2011; Hoogkamer et al., 2017), people within the triathlon community are starting to wonder whether it would be possible to break the 7-h mark for the IM distance. Projects such as the *Breaking 2* financed by Nike, and the *Ineos 1:59 challenge*, supported by the chemical company Ineos, are events put in place with the goal of creating a hype surrounding an extraordinary sporting feat, which, ultimately, are used by the supporting companies as promotional vehicles and marketing opportunities. Recently, the campaign ≪ *Defy the Impossible* ≫ from which derives the ≪ *Sub 8* ≫ and ≪ *Sub 7* ≫ projects, the latter which represents the main focus of this article, were created with the goal of breaking sometime in 2022 the 7-h barrier for the men and the 8-h barrier for the women for an IM.

We are aware of no scientific writing which attempted to detail from a theoretical point of view whether the breaking of the 7-h mark for the IM is possible. Therefore, the first objective of this article was to elucidate, through the use of predictive analyses, whether an IM distance triathlon under 7-h might be achieved in 2022 without external assistance and with the current swimming, cycling, and running equipment. Our different analyses showed that this is very unlikely, which led to the second goal of this paper that was to demonstrate

1 For the purpose of this article, the time of 7 h 27 min and 53 sec will be considered as the current world record, since the swim was not current-assisted.

how external aid should be deployed to achieve the breaking of the 7-h mark. The last part of this article is dedicated to race organizers and expose the key course characteristics and meteorological conditions we believe are required to optimize the chance of success of this event.

Is a sub 7-h IM possible?

Such to determine whether a sub 7-h IM distance triathlon is achievable without any external help and while using the currently available racing equipment, we used different predictive approaches where we first analyzed the evolution of the fastest times recorded in the history of the IM since 1989 (prior to 1989, archives related to the IM best times are largely missing). Second, we looked at the progression of the racing times registered at the IM event held in Roth from 1990 to 2019, which is recognized as one of the fastest IM race-course in the world. Third, we summed the best swimming, running, and cycling times clocked from all IM races confounded since the inception of the distance. And finally, we predicted the best possible time that could be achieved for the IM distance when doubling the half-IM world record time, while correcting for a computed slowing factor inherent to the doubling of the distance.

Evolution of the fastest IM times from 1989 to 2021

Table 1 reports the best IM completion times from 1989 to 2021. A time of 7-h would represent an improvement of 6.6% compared to the current world record of 7 h 27 min and 53 sec, which is of considerable importance provided that from 1989 to 2021, the IM world record has only improved by 7.5%, as can be computed from observations made in Table 1. Based on the evolution of the IM world record times over those years, the racing times declined only on average by 1 min and 03 sec per year. Figure 1A illustrates a scatterplot showing the evolution of the IM world record times between 1989 and 2021. The trend of the regression line suggests that there is still room for improving the IM world record time; indeed, over the past 10 years, each new world record has fallen from the previous by an average of ∼6 min. Moreover, the time improvement over that time-period has been of ∼18 min, compared to ∼16 min over the previous 20 years. Interestingly, the regression line predicts that in 2022 the fastest IM time is expected to be between 7 h 39 min and 59 sec and 7 h 26 min and 35 sec, the latter which is 0.3 % faster than the current world record, which was achieved during an event specifically designed to break the previous world record of 7 h 35 min and 39 sec. However, this time is still significantly slower than a sub 7-h IM. Importantly, based on the calculated trend from the best IM finishing times observed over the past 32 years, a sub 7-h IM completed without external assistance could theoretically not be achieved at least before the year 2049.

TABLE 1 World record Ironman^{TM} triathlon performances.

Year	Athletes	Location	Total time (h:min:sec)
1989	Dave Scott	Lake Biwa, Japan	8:01:32
1996	Lothar Leder	Roth, Germany	7:57:02
1997	Luc Van Lierde	Roth, Germany	7:50:27
2011	Marino Vanhoenacker	Klagenfurt, Austria	7:45:58
2011	Andreas Raelert	Roth, Germany	7:41:33
2016	Jan Frodeno	Roth, Germany	7:35:39
2021	Jan Frodeno	Algäu, Germany	7:27:53
2021	Kristian Blummenfelt	Cozumel, Mexico	7:21:42*

*For the purpose of this article, the time of 7 h 21 min and 42 sec achieved by Kristian Blummenfelt is not considered the world record since the swim was current-assisted.

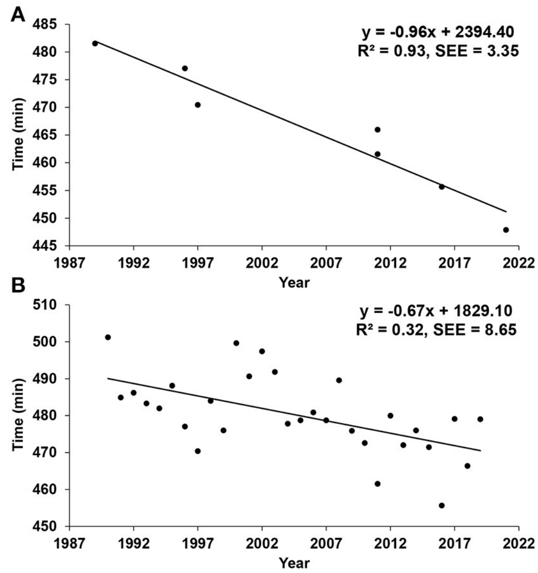

FIGURE 1
(A) Prediction of the best Ironman^{TM} finishing time from the best times achieved over the distance from 1989 to 2021. **(B)** Prediction of the best Ironman^{TM} finishing time from the best times achieved each year over the distance during IM Challenge Roth from 1990 to 2019. SEE, standard error of the estimate.

IM Challenge Roth: Racing time progression between 1990 and 2019

IM Challenge Roth has produced the most IM world records since 1990; therefore, we believe that these numbers represent a good source of information for estimating when a sub 7-h IM may be accomplished. Table 2 demonstrates the winners'

TABLE 2 Evolution of the racing time of the winners of the Challenge Roth Ironman[TM] triathlon from 1990 to 2019.

Years 1990–1999	Total time (h:min:sec)	Years 2000–2009	Total time (h:min:sec)	Years 2010–2019	Total time (h:min:sec)
1990	8:21:13	2000	8:19:38	2010	7:52:36
1991	8:04:54	2001	8:10:39	2011	7:41:33
1992	8:06:12	2002	8:17:25	2012	7:59:59
1993	8:03:19	2003	8:11:50	2013	7:52:01
1994	8:01:59	2004	7:57:50	2014	7:56:00
1995	8:08:07	2005	7:58:45	2015	7:51:28
1996	7:57:02	2006	8:00:52	2016	7:35:39
1997	7:50:24	2007	7:58:45	2017	7:59:07
1998	8:03:59	2008	8:09:34	2018	7:46:23
1999	7:56:00	2009	7:55:53	2019	7:59:02

completion times for IM Challenge Roth from 1990 to 2019.[2] The slowest and fastest times achieved over this timespan were respectively 8 h 21 min and 13 sec and 7 h 35 min and 39 sec. Hence, an improvement in time of 10%, or 1 min 30 sec per year was observed over this period of 30 years, which fits nicely well with the results observed regarding the improvement in IM world record times between 1989 and 2021. As shown in Figure 1B, a regression line built from the winning times over the past 30 years at IM Challenge Roth demonstrates that the breaking of the 7-h barrier for IM Roth is unlikely to occur at least prior to 2077, based on an associated measurement time error of ±17 min and 17 sec.

Summation of the world's fastest IM swimming, running, and cycling times

Another reasonable way to estimate whether a sub 7-h IM is possible without external assistance is to combine and sum the world's fastest IM swimming, cycling, and running times ever achieved by any given athletes in any given IM races. Because these times were presumably achieved by discipline specialists and potentially under the best conditions possible, it is very unlikely that even with the best preparation possible a single IM triathlete could align and match or even best each of those times.

The fastest, non-current-assisted swimming time in an IM triathlon was achieved with a wetsuit, in a lake, by Jan Sibbersen, in a time of 42 min and 17 sec in 2004. The fastest official cycling time in an IM, achieved at the ZTBR in 2021 by Jan Frodeno, is 3 h 55 min and 22 sec.[3] Finally, Gustav Iden completed the fastest official IM marathon time (2 h 34 min and 50 sec) in 2021 at IM Florida.[4] The summation of these times, i.e., 7 h 12 min and 29 sec, reveals the fact that even the best times achieved over time within each of the disciplines that make up triathlon would not be sufficient to break the 7-h mark. And one must take into account that this overall time does not include the transition times.

Prediction of IM time from the half-IM world record time

The current half-IM world record is held by Kristian Blummenfelt. The Norwegian athlete completed the 2018 Bahrain half-IM in a time of 3 h 29 min and 04 sec. This figure highlights the fact that an athlete looking to break the 7-h mark would need to sustain that pace for twice the distance, which would represent an extraordinary accomplishment. Indeed, by doubling the swimming, cycling, and running times a total racing time of 6 h 54 min and 38 sec is obtained.[5] However, as shown in Table 3, when the fastest IM and half-IM times of the current top 20 triathletes in the world competing in both IM and half-IM are compared, it can be observed that, on average, the IM time is 7.3 ± 4.2% slower than the doubling of the half-IM time.[6] Based on this slowing factor, our calculations indicate that Blummenfelt's predicted IM time would be 7 h 24 min and 58 sec, with a margin of error of ±18 min and 38 sec. Blummenfelt completed his first IM in 2021 (with a current-assisted swim) with a time of 7 h 21 min and 12 sec. Therefore, in order to

2 The 2021 times are not included since the race-course was shorter due to construction work.

3 The time of 3 h 54 min and 59 sec achieved by American Andrew Starykowicz at IM Florida in 2018 is not considered as the fastest cycling time since the legitimacy of this record is in question because the cycling distance of this triathlon may have been slightly shorter than 180 km.

4 The fastest unofficial marathon time in an IM is 2 h 34 min and 39 sec and it is held by American Matt Hanson and was achieved at IM Texas. However, the legitimacy of the distance is in question.

5 Doubling the half-IM time and subtracting an average total transition time of 3 min and 30 sec.

6 A factor of 5.4% was calculated by Thorsten Raddle (Trirating, 2018) by using a total of 107 data points.

TABLE 3 Comparison of the fastest half-Ironman™ and Ironman™ triathlons of some of the best current long-distance triathletes in the world.

Athletes	Half-IM best times (h:min:sec)	Doubling of the Half-IM best times (h:min:sec)*	IM best times (h:min:sec)	Difference (%)†
Andreas Dreitz	3:40:12	7:16:54	7:53:06	7.7
Bart Aernouts	3:44:38	7:25:46	7:55:12	6.2
Braden Currie	3:23:33	6:43:36	7:54:58	15
Daneil Baekkegard	3:29:18	6:55:06	7:52:58	12.2
Denis Chevrot	3:41:14	7:18:58	7:51:00	6.8
Florian Angert	3:41:27	7:19:24	7:45:05	5.5
Gustav Iden	3:29:25	6:55:20	7:42:56	10.3
Jackson Laundry	3:39:50	7:16:10	8:26:00	13.8
Jan Frodeno	3:36:31	7:09:32	7:27:53	4.1
Jan Van Berkel	3:40:49	7:18:08	7:39:40	4.7
Joe Skipper	3:55:32	7:47:34	7:53:52	1.3
Kristian Hogenhaug	3:50:37	7:37:44	7:37:46	0
Kyle Smith	3:39:43	7:15:56	8:08:53	10.8
Leon Chevalier	3:50:20	7:37:10	7:57:02	4.2
Lionel Sanders	3:38:18	7:13:06	7:43:30	6.6
Matt Hanson	3:46:48	7:30:06	7:39:25	2
Patrick Lange	3:43:46	7:24:02	7:45:21	4.6
Rasmus Svenningsson	3:29:18	6:55:06	7:51:33	12
Sam Appleton	3:43:58	7:24:26	8:09:54	9.3
Sam Long	3:37:34	7:11:38	7:55:33	9.2
Average	**3:40:09**	**7:16:47**	**7:51:35**	**7.3 ± 4.2**&

*Half-IM time × 2, substracting a time of 3 min and 30 sec for the transition times.
† IM best time–doubling of the half-IM best time.
& Average ± standard deviation.

break the 7-h barrier, he would need to be 5.9% faster than his predicted time, which is very unlikely considering, as reported above, that the IM world record has only improved by 7.5% over the past 32 years.

Based on the computations presented above, we can therefore conclude with relative confidence that a sub 7-h IM is very unlikely to be achieved without external assistance anytime soon. But a question remains; is it even reasonable to believe that an IM under 7-h could be completed with external help. The next part of the article will focus on this given question.

Can a sub 7-h IM be achieved with assistance?

A prerequisite to the determination that an IM could indeed be achieved in or under a time of 7-h is to first correctly partition the amount of time that should be attributed to each of the single parts of the race, that is the swimming, cycling, running and transition times. We underwent this exercise by contrasting the finishing times for each of the three disciplines in relation to the total finishing times of the winner of the IM Challenge Roth triathlon from 1990 to 2019. As demonstrated in Table 4, we determined that the swimming, cycling, and running times represent, on average, 10.2, 54.9, and 34.9% of the total completion time of an IM, with a standard deviation for each of the three disciplines ≤1%, which underlines the robustness of these observations. From those calculations, a single triathlete performing a 7-h IM would likely achieve times in the vicinity of 42 min and 32 sec for swimming, 3 h 49 min and 32 sec for cycling and 2 h 25 min and 47 sec for running, and the total transition times would need to be <2 min. It immediately jumps to the eyes that this triathlete would require to produce world-record swimming, cycling, and running performances to achieve a sub 7-h IM; this is unlikely to occur in 2022, nor in the near future as well. But those theoretical numbers do expose one important factor in that a sub 7-h IM could only be accomplished with outside help and if substantial time deficits are made during the cycling portion of the race. Indeed, although it is reasonable to believe that a strong swimmer could meet the targeted swimming time of ∼42-43 min, it would be utopic to consider that a sub 2 h and 26 min marathon time is achievable.

TABLE 4 Time for each discipline of the winners of the Ironman™ Challenge Roth triathlon from 1990 to 2019 in relation to total racing time.

Years	Total time (h:min:sec)	Swim (h:min:sec)	% Swim	Cycle (h:min:sec)	% Cycle	Run (h:min:sec)	% Run
1990	8:21:13	0:49:14	9.82	4:43:30	56.56	2:48:29	33.61
1991	8:04:54	0:49:38	10.24	4:30:26	55.77	2:44:50	33.99
1992	8:06:12	0:50:52	10.46	4:29:38	55.46	2:45:24	34.02
1993	8:03:19	0:53:23	11.04	4:21:04	54.02	2:48:51	34.94
1994	8:01:59	0:49:41	10.31	4:23:53	54.75	2:48:25	34.94
1995	8:08:07	0:51:11	10.49	4:20:28	53.36	2:56:28	36.15
1996	7:57:02	0:49:33	10.39	4:24:06	55.36	2:43:23	34.25
1997	7:50:24	0:44:51	9.53	4:28:47	57.14	2:36:49	33.34
1998	8:03:59	0:48:16	9.97	4:23:02	54.35	2:52:41	35.68
1999	7:56:00	0:50:59	10.71	4:15:47	53.74	2:49:13	35.55
2000	8:19:38	0:47:43	9.55	4:31:18	54.3	3:00:37	36.15
2001	8:10:39	0:46:51	9.55	4:33:09	55.67	2:50:37	34.77
2002	8:17:25	0:50:50	10.22	4:32:09	54.71	2:54:26	35.07
2003	8:11:50	0:50:42	10.31	4:28:57	54.68	2:52:08	35
2004	7:57:50	0:47:59	10.04	4:28:27	56.18	2:41:22	33.77
2005	7:58:45	0:47:33	9.93	4:24:32	55.25	2:46:38	34.81
2006	8:00:52	0:46:53	9.75	4:27:51	55.7	2:46:06	34.54
2007	7:58:45	0:49:45	10.39	4:17:58	53.89	2:46:39	34.81
2008	8:09:34	0:48:47	9.96	4:31:59	55.55	2:48:49	34.48
2009	7:55:53	0:50:30	10.61	4:22:56	55.25	2:42:30	34.15
2010	7:52:36	0:46:51	9.91	4:24:48	56.03	2:40:53	34.04
2011	7:41:33	0:46:18	10.03	4:13:11	54.85	2:42:06	35.12
2012	7:59:59	0:47:41	9.93	4:31:07	56.49	2:41:13	33.59
2013	7:52:01	0:46:05	9.76	4:16:24	54.32	2:49:35	35.93
2014	7:56:00	0:48:58	10.29	4:21:23	54.91	2:45:40	34.8
2015	7:51:28	0:47:33	10.09	4:10:55	53.22	2:53:02	36.7
2016	7:35:39	0:45:22	9.96	4:09:25	54.74	2:40:36	35.25
2017	7:59:07	0:52:55	11.05	4:20:42	54.41	2:45:28	34.54
2018	7:46:23	0:47:59	10.29	4:09:30	53.5	2:48:57	36.23
2019	7:59:02	0:51:28	10.74	4:14:59	53.23	2:52:38	36.04
Average ± SD (%)			**10.2 ± 0.4**		**54.9 ± 1.0**		**34.9 ± 0.9**

SD, standard deviation.

In the next sections, an attempt will be made to demonstrate that with external assistance mostly through drafting during the swimming, cycling, and running parts of the race to overcome water or air resistance, a completion time of 7-h for the IM is possible. The different variables that can help make a sub 7-h IM performance possible are summarized in Figure 2. However, this IM performance would not be considered an official IM record according to the World Triathlon Corporation rules. Similarly, the sub 2-h marathon achieved by Eliud Kipchoge is not considered eligible as an official world record. In the current paper, ≪ assistance ≫ is defined as any means that an athlete could be using to maximize its swimming, running and cycling velocity, excluding, however, all forms of help coming from water current, a significant negative elevation for the cycling and the run, magnets or equipment running on or requiring a source of energy from the sun, electricity, gazes or batteries. The term ≪ racing triathlete ≫ is used to refer to the triathlete identified to attempt the breaking of the 7-h mark.

Swimming

Table 5 shows the best swimming times realized in an IM for each of the years between 2005 and 2021. As mentioned previously, Jan Sibbersen owns the fastest swimming time (Trirating, 2022). What is remarkable is that his record has not been beaten since. It is worth highlighting the fact that this triathlete has been a national level swimmer for 10 years

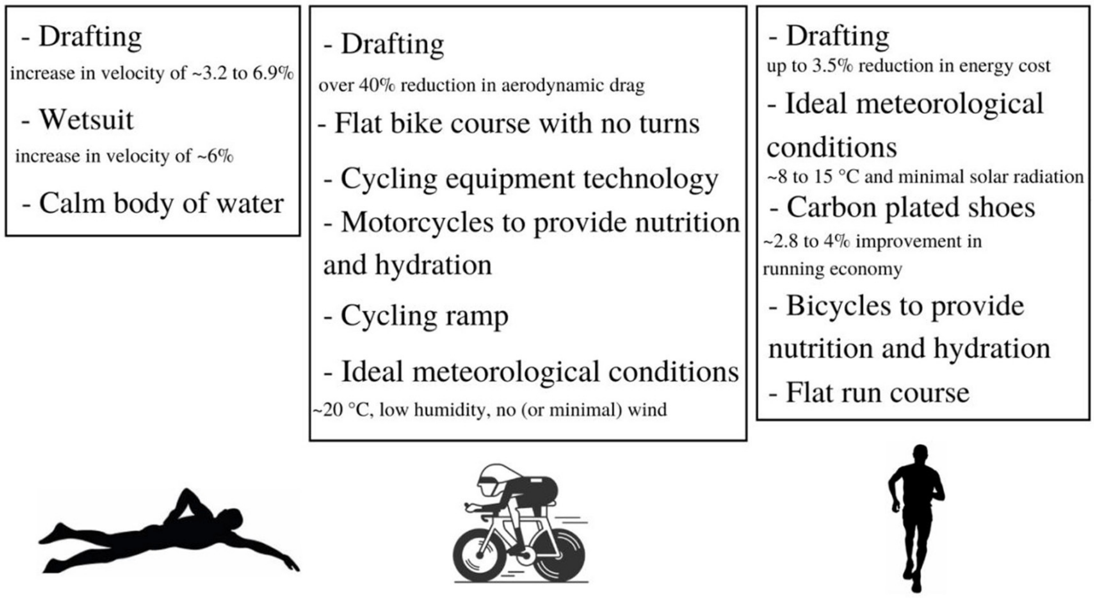

FIGURE 2
Summary of the different variables that can make a sub-7 Ironman^{TM} performance possible.

and has achieved personal best times in a 50-meter pool of 1 min and 52 sec for the 200 m, 3 min and 56 sec for the 400 m and 15 min and 47 sec for the 1500 m (Sailfish, n.d.). This may explain why this record still stands. Nevertheless, in 2010 and 2013, wetsuit-assisted swimming times close (< 43 min) to that of Sibbersen have been realized by swimmers with no particular competitive background in swimming, at least to our knowledge. Taken together, these information show that without the wearing of a wetsuit, an athlete attempting to break the 7-h barrier is very unlikely to achieve the targeted time of 42 min and 32 sec. Moreover, it seems that an IM swimming time < 43 min represents an exception confirming the rule, i.e., that it is tremendously difficult to realize. However, as will be demonstrated below, a strong swimmer capable of achieving a lake- or ocean-based, wetsuit-assisted swimming time of 46-47 min for the 3.8 km distance could potentially achieve this targeted time with the appropriate external help.

TABLE 5 Yearly fastest swimming times in an Ironman^{TM} between 2005 to 2021.

Year	Athletes	Event	Time (min:sec)
2005	Jan Sibbersen	IM Austria	44:14
2006	Gilles Reboul	IM France	44:18
2007	Bryan Rhodes	IM United Kingdom	44:39
2008	Andi Boecherer	IM Germany	43:55
2009	John Flanagan	IM Louisville	44:54
2010	Luke McKenzie	IM Brasil	42:26
2011	Clayton Fettell	IM Cairns	43:48
2012	Luiz Francisco Ferreira	IM Brasil	44:04
2013	Bart Colpaert	IM Austria	42:54
2014	Luiz Francisco Ferreira	IM Austria	44:17
2015	Dylan McNeice	IM New Zealand	44:26
2016	Dylan McNeice	Challenge Wanaka	43:30
2017	Luiz Francisco Ferreira	IM Brasil	44:12
2018	Jesper Svensson	IM Brasil	43:47
2019	Thomas Davis	Challenge Anhui	43:48
2020	Josh Amberger	IM Cairns	45:41
2021	Josh Amberger	IM Cairns	43:28

Energy cost of swimming

Swimming performance is optimized when propelling cost is maximally reduced. From a pure mathematical standpoint, the energy cost of swimming is calculated by dividing oxygen consumption at a steady state by the corresponding velocity (Zamparo et al., 2005). The energy cost of swimming depends on propelling efficiency, which represents the amount of work necessary to overcome hydrodynamic resistance in relation to the total work required to cover a given distance. Increasing swimming velocity will increase the work necessary to overcome hydrodynamic resistance as the latter increases with the square of the velocity. In addition to the improvement of swimming technique, the wearing of a wetsuit (de Lucas et al., 2000; Zamparo et al., 2005; Tomikawa et al., 2008;

Peeling and Landers, 2009) and drafting lead swimmers (Bassett et al., 1991; Chatard et al., 1998; Brisswalter and Hausswirth, 2008) have been shown to reduce the work to overcome hydrodynamic resistance and therefore reduce the energy cost of swimming.

Wetsuit

Wearing a wetsuit allows the swimmer to be more horizontal and higher relative to the water surface which, in turn, will act to reduce hydrodynamic resistance (de Lucas et al., 2000; Peeling and Landers, 2009) and the required energy to complete a swimming distance. However, the extent of these effects is dependent upon intrinsic factors related to swimmers such as the swimming technique, propelling efficiency and buoyancy (Chatard et al., 1995). Wearing a wetsuit has been demonstrated to reduce the cost of swimming at 80% of maximal oxygen consumption ($\dot{V}O_{2max}$) by ∼7.5% (Tomikawa et al., 2008) and to increase velocity by ∼6% (Gay et al., 2020).

Drafting

A lead swimmer creates a depression in the water behind him, which generates a low-pressure gradient. Therefore, the swimmer drafting a lead swimmer encounters lower resistive body drag (Hausswirth and Brisswalter, 2008). The reduction in drag is estimated to vary between ∼10 to 26% (Bentley et al., 2007). Many studies have observed lower lactate levels, ratings of perceived exertion and oxygen consumptions when drafting compared to swimming at the same velocity without drafting (Bassett et al., 1991; Chatard et al., 1998). As a result, drafting has been demonstrated to reduce the metabolic cost of swimming by ∼5 to 10% and increase velocity by ∼3.2 to 6.9% (Bentley et al., 2007). Importantly, the energy saved by drafting a lead swimmer can also have a positive impact on the bike and run portions of the race. Indeed, Delextrat et al. (2003) have observed a 4.8% increase in cycling efficiency after swimming 750 meters at competition pace while drafting a swimmer, compared to without drafting.

Taken altogether, these observations unequivocally illustrate that an acceptable swimming time for an athlete attempting to break the 7-h mark can only be achieved while wearing a wetsuit and using lead swimmers. Considering that the use of drafting could improve swimming performance by an upper limit of 6.9%, then an accomplished swimmer with a demonstrated capacity to achieve a wetsuit-assisted swimming time of 46-47 min during an IM should expect to achieve a swimming time in the vicinity of 42 min and 50 sec to 43 min 45 sec with proper drafting. A swimming time slightly over these figures should not be problematic as important time gains are possible on the bike.

Cycling

Cycling is the discipline that is the longest, both in distance and in time in an IM. According to Sousa et al. (2019), it is the part of the race that better predicts the total time to complete the distance ($R^2 = 0.69$; $p < 0.001$), followed by running ($R^2 = 0.52$; $p < 0.001$) and swimming ($R^2 = 0.23$; $p < 0.001$). As reported above, our calculation indicates that in order to break the 7-h barrier a triathlete would need to complete the 180 km cycling distance in a time faster than 3 h 49 min and 32 sec such to compensate for the possible time lost accrued during the swimming and running portion of the race vs. the theoretical times. Therefore, the racing triathlete would need to cycle at a velocity > 47.1 km·h^{-1}. In comparison, the fastest official time in an IM is 3 h 55 min and 22 sec (45.9 km·h^{-1}). This would therefore represent an improvement in cycling time of over 2.5% compared to the actual fastest cycling time achieved in an IM. Table 6 demonstrates the improvement in cycling world record times in an IM between 2005 and 2021. Impressively, between those years, the cycling time fell by 10%. This is likely due to new improvements in technology. Interestingly, the actual record improved over the previous one by 2.4%, which is impressive. However, the use of motorcycles to provide nutrition and hydration, and of a cycling ramp, similar to a velodrome ramp, to allow the triathletes to do a 180° turn without having to slow down, may have been the key contributing factors for the achievement of this fast cycling time. We believe that shaving another 2.5% (or 5 min and 53 sec) off the actual world record may be difficult to reach in 2022 without special accommodations or exceptional race circumstances.

There are three main resistive forces encountered when cycling that influence the power that a cyclist needs to generate to move forward: (1) rolling resistance, (2) gravity and, (3) air resistance (Martin et al., 1998; Crouch et al., 2017). Reducing to a minimum the impact of these forces on the bike and cyclist is the key for the achievement of fast cycling times. The next sections provide cues on how to minimize the effect of resistive forces while cycling and demonstrate how the use of drafting would permit to perform the 180 km portion of the IM at the velocity required to race a sub 7-h IM.

Rolling resistance and gravity

The wheels are in contact with the road during cycling, which creates resistance. The rolling resistance is affected by the tire pressure and the vertical load applied on the tire. The vertical load is impacted in proportion to the weight of the cyclist and bicycle (Grappe et al., 1999). However, by optimizing the choice of tire and tire pressure and by choosing a bike course with excellent road surface conditions, it is possible to limit the rolling resistance to a minimum. Of course, the ideal race-course should include minimal elevation gains as the force required to move a bike uphill against the force of gravity is substantially more than

TABLE 6 World record cycling times in an Ironman™ since 2005.

Year	Athletes	Event	Type of bike course	Time (h:min:sec)
2005	Torbjorn Sindballe	IM World Championships Hawaii	Flat roads with rolling hills	4:21:36
2006	Mitchell Anderson	IM Western Australia	Flat roads	4:18:07
2007	Thomas Hellriegel	Challenge Roth	Flat roads with rolling hills	4:16:18
2009	Normann Stadler	Challenge Roth	Flat roads with rolling hills	4:14:42
2010	Sebastian Kienle	Challenge Roth	Flat roads with rolling hills	4:14:07
2011	Andreas Raelert	Challenge Roth	Flat roads with rolling hills	4:11:43
2012	Andrew Starykowicz	IM Florida	Flat highway	4:04:39
2013	Andrew Starykowicz	IM Florida	Flat highway	4:02:17
2017	Andrew Starykowicz	IM Texas	Flat highway	4:01:14
2021	Jan Frodeno	Zwift Tri Battle Royale	Flat roads	3:55:22

that required to ≪ fight ≫ rolling resistance or air resistance. On a flat bike course with an ideal road surface condition, the cyclist weight as well as the bicycle weight will have a minimal impact on performance.

Air resistance

The aerodynamic drag (the force applied by the air on an object to resist its motion) depends on the drag coefficient (the efficiency with which an object passes through the surrounding air) and frontal area of the cyclist, the air density and the relative wind speed (Griffith et al., 2014; Crouch et al., 2017). Since aerodynamic drag increases with the square of relative wind speed, as a cyclist goes faster, air resistance becomes a greater factor affecting his rate of forward progression (Faria et al., 2005). At a velocity of 30 km·h^{-1}, air resistance represents about 80% of the resistive force encountered by a cyclist (di Prampero, 2000), and up to 90% of the resistive force at higher velocities (Grappe et al., 1997; Griffith et al., 2014).

The drag area represents the combination effect (product) of the drag coefficient and frontal area (Barry et al., 2015a). The drag coefficient depends on body geometry and it is lower for streamlined objects such as an airfoil or a car (Barry et al., 2015b). A cyclist should try to reduce its frontal area and streamline his geometry without compromising too much comfort and the ability to generate power. Indeed, about 80% of the aerodynamic drag of a cyclist on a bicycle is due to the cyclist and the remainder is related to the bicycle, the wheels and the accessories such as the water bottle position on the bicycle (Crouch et al., 2017). Small changes to a cycling position, especially to the placement and angle of the handlebars, can reduce the drag area such to confer a 60-sec improvement over a 40 km time trial, which would translate to a 4 min and 30 sec improvement over 180 km (Jeukendrup and Martin, 2001).

Triathletes use bicycles designed to reduce aerodynamic drag. Indeed, they have an aerodynamic frame, handlebars designed for time trialing and lenticular wheels, which, in total, can save about 60 W of power output at a velocity of 50 km·h^{-1} (Jeukendrup and Martin, 2001). Triathletes competing in IM triathlons do not need to comply with the International Cycling Union (UCI) rules regarding the cyclist position and the cycling equipment (García-López et al., 2008). Therefore, they can optimize their position to reduce their aerodynamic drag as much as possible.

Drafting

Drafting behind another cyclist can significantly reduce air resistance (Blocken et al., 2013), but it is not allowed in IM triathlons. However, if external assistance is used for the *sub 7 project*, a group of cyclists could ride in front of the racing triathlete which would allow him to ride at a significantly higher speed and reduce energy expenditure, oxygen consumption (Lukes et al., 2005), heart rate, lactate concentration and perceived exertion, which would also allow the racing triathlete to run faster after cycling (Hausswirth et al., 2001).

The magnitude of the effect of drafting may depend on many factors, such as the number of cyclists in the group, the position of the cyclists, the distance between each cyclist as well as the drag area of the lead cyclists (Lukes et al., 2005). A cyclist drafting as closely as possible behind a lead cyclist may experience a drag reduction of as much as 15-50%, which may reduce to 10-30% at a distance of one bicycle (Crouch et al., 2017). Barry et al. (2015a) studied the aerodynamic drag of 4 cyclists riding in a time-trial position in a team pursuit position. The four riders experienced, respectively, an average drag saving of 5, 45, 55, and 57% at a speed of 65 km·h^{-1}. Therefore, a time significantly faster than the theoretical time previously calculated (time of 3 h 49 min and 32 sec) could be achieved.

By taking into consideration body weight, equipment weight, coefficient of drag (CDA), air density (Rho), rolling resistance and slope, we estimated the power output required

TABLE 7 Modulation of the cycling time and power output based on different drag coefficient scenarios and on different power reductions from drafting.

Variables	Scenario 1	Scenario 2
Cyclist weight (kg)	74	74
Equipment (bicycle, wheels, etc.) weight (kg)	8	8
Total weight (kg)	82	82
Frontal area (m^2)	0.3	0.32
Drag coefficient (dimensionless)	0.7	0.7
Drag coefficient x frontal area (CdA)	0.21	0.224
Air density (Rho) (kg/m^3)	1.226	1.226
Rolling resistance (dimensionless)	0.004	0.004
Slope G (%)	0	0
Cycling time (h:min:sec)	**Power output (W)**	
4:00:00	292	308
3:55:00	309	327
3:50:00	328	347
3:49:32	330	349
3:40:00	370	390
3:40:00 with drafting (assuming 35 % power reduction)	256	268
3:40:00 with drafting (assuming 40 % power reduction)	240	251

to complete the cycling portion of the race in different times (between 4 h 00 and 3 h and 40 min) (Table 7) (Martin et al., 1998). For the purpose of illustration, the calculations were done using a body mass of 74 kg and 2 estimated drag coefficients. Based on these numbers, and assuming a conservative reduction in power output of 35-40% due to drafting, the racing triathlete would only need to maintain a power output of 240-268 W to complete the 180 km in 3 h and 40 min, which would be significantly less than the power output required if he were to ride without drafting estimated to be between 370 and 390 W. In turn, this highlights the fact that the alternating lead cyclists would have to be capable of sustaining that amount of power. Hence, it must be borne in mind that, ultimately, the rate of progression of the racing triathlete will be dictated by the quality of the lead cyclists. Indeed, in order to be able to push a power output of 370–390 W for a few minutes when leading the group, the lead cyclists would need to have a critical power (CP) higher than 390 W, which can be expected of professional cyclists (World Tour of professional-continental cyclists) (Bartram et al., 2018).

TABLE 8 Yearly fastest Ironman™ running times between 2005 and 2021.

Year	Athletes	Event	Time (h:min:sec)
2005	Gerrit Schellens	IM Lanzarotte	2:44:29
2006	Gerrit Schellens	IM Switzerland	2:43:45
2007	Chris McCormack	IM World Championship Hawaii	2:42:02
2008	Timo Bracht	IM Germany	2:42:33
2009	Michael Goehner	Challenge Roth	2:41:17
2010	Rasmus Henning	Challenge Roth	2:39:43
2011	Mads Vittrup	IM Copenhagen	2:38:58
2012	Craig Alexander	IM Melbourne	2:38:46
2013	Bart Aernouts	IM France	2:37:01
2014	Jeff Symonds	IM Canada	2:40:34
2015	Victor Del Corral	IM France	2:42:04
2016	Joe Skipper	Challenge Roth	2:38:52
2017	Patrick Lange	IM World Championship Hawaii	2:39:59
2018	Jan Frodeno	IM Germany	2:39:06
2019	Ben Hoffman	IM Florida	2:36:09*
2020	Matt Hanson	IM Florida	2:41:57
2021	Gustav Iden	IM Florida	2:34:50*

*Represents a new world record.

Running

In 1997, Luc Van Lierde achieved an outstanding IM world record marathon time of 2 h 36 min and 49 sec. So special was this record that it stood for 22 years until it was beaten in 2019 by a scarce 40 sec. Since then, the world record has improved by another 1 min and 19 sec. Table 8 demonstrates the fastest IM marathon times reached for each of the years between 2005 and 2021. What it clearly illustrates is that running an IM marathon $<$ 2 h and 35 min represents and extraordinary accomplishment that has only been realized on one occasion since the inception of this distance.

According to our estimation, the IM marathon time of a single triathlete performing a 7-h IM would need to be 2 h 25 min and 47 sec, corresponding to a mean velocity of 4.8 $m{\cdot}s^{-1}$ (17.4 $km{\cdot}h^{-1}$) or a pace of 3 min and 27 $sec{\cdot}km^{-1}$. This is about 9 min faster (5.8%) than the fastest marathon time ever recorded in an IM (2 h 34 min and 50 sec) and is much faster than the computed theoretical marathon time. This time is so far off from what history tells us can be achieved that it is very unlikely to be accomplished, even with drafting. Moreover, as this is the last part of the race and time deficits could quickly accumulate if the racing triathlete fatigues prematurely or has a ≪ bad ≫ running day, room for errors is required. However, with external assistance where a time of 3 h and 40 min is tenable on the bike, the racing triathlete would still need to run very fast but complete the marathon in a more ≪ reasonable time ≫ of 2 h 35 min 30 sec (considering a 42 min 32 sec swim time and a total transition time of 2 minutes), which is 40 seconds slower than the fastest marathon time ever recorded in an IM (2 h 34 min and 50 sec).

Among the three main physiological determinants of running performance, which are $\dot{V}O_{2max}$, lactate threshold and running economy (Joyner et al., 2011), the latter is likely to play the most important role (Saunders et al., 2004). It is defined as the rate of oxygen consumption or energy expenditure spent per unit of distance (Lacour and Bourdin, 2015; Hoogkamer et al., 2017). Therefore, an improvement in running economy indicates that less energy is expended for running at a given speed. Hence, to meet the optimal running time the racing triathlete should do whatever he can to optimize running economy. Many factors can affect running economy, including body weight, leg architecture, muscle fibers composition (Kyröläinen et al., 2000; Lacour and Bourdin, 2015) and the mechanical and morphological properties of the muscle tendon-units (Arampatzis et al., 2006; Kubo et al., 2010; Albracht, K., and Arampatzis, 2013). Albeit triathletes may exercise a certain control over the first factor, i.e., body weight, they certainly have little influence over the remainder factors which are, for the most part, genetically determined. Moreover, triathletes are generally heavier than elite runners because of the upper body muscles required for swimming which affects their running economy.

Running economy could negatively be impacted after swimming and cycling at a high intensity due to muscle damage (Bessa et al., 2008; Lacour and Bourdin, 2015), neuromuscular fatigue (Lepers et al., 2000), elevated core temperature and possibly dehydration (Hausswirth and Lehenaff, 2001). However, the impact of these factors could be substantially dampened if the racing triathlete drafts other cyclists during the cycling part of the race (Bentley et al., 2002). Indeed, under this circumstance, the rate of energy expenditure during cycling would be significantly less, thereby reducing muscle stress and fatigue, the rate of increase in core temperature and subsequently the rate of sweat loss and dehydration.

Running economy will be expected to slowly deteriorate during the marathon (Hausswirth et al., (1996); Guezennec et al., 1996; Hausswirth and Lehenaff, 2001) due to ongoing muscle damage and muscle glycogen depletion (Assumpção et al., 2013). Indeed, based on Brueckner's (1991) findings, energy expenditure is expected to increase by at least 3% over the course of the marathon. This is due, in part, by a change in the running kinematics, such as a greater forward lean (Hausswirth et al., 1997), an increase in stride time variability (Connick and Li, 2015), a decrease in stride length and an increase in stride frequency (Gottschall and Palmer, 2000; Kyröläinen et al., 2000; Place et al., 2004; Connick and Li, 2015).

Fortunately, there are some tools available to triathletes to minimize the decline in running economy that inevitably occurs during the marathon part of an IM. These are discussed in the following lines.

Running Shoes

Running economy can be impacted by the biomechanical advantage provided by shoe technology. Since 1960, when Abebe Bikila ran barefoot to set the world record in 2 h 15 min and 16 sec (Hoogkamer et al., 2017), running shoes have evolved from an ethylene-vinyl acetate (EVA) cushioning to air-cushioned materials. Worobets et al. (2014) observed a 1% improvement in running economy between the Adidas boost midsole and a standard EVA cushioning, which is due to a ≪ superior energy storage/return ≫ in the midsole foam (Hoogkamer et al., 2019). This energy storage/return effect of the midsole foam compensates for the detrimental impact of the slightly higher shoe weight, compared to a more minimalist shoe or to running barefoot (Tung et al., 2014; Hoogkamer et al., 2016).

Furthermore, high-tech running shoes nowadays have a carbon plate midsole, which improves their binding stiffness. The carbon fiber plate (CFP) has a ≪ clever lever effect ≫ on the ankle joint mechanism and it has a ≪ stiffening effect ≫ on the metatarsophalangeal joint (Hoogkamer et al., 2019; Nigg et al., 2020; Cigoja et al., 2021). The carbon fiber plate combined with the superior midsole foam result in an improvement in running economy of between 2.8 (Hunter et al., 2019) and more than 4% (Hoogkamer et al., 2018; Barnes and Kilding, 2019), which translates into an improvement in running performance greater than 2% (Muniz-Pardos et al., 2021). Since the introduction of the carbon fiber plate shoes in 2016, all the women's and men's world record in distance ranging from the 5 km to the marathon have been broken (Bermon et al., 2021; Muniz-Pardos et al., 2021).

Drafting

The running energy cost can also be reduced by drafting other runners. Since the running speed is considerably less than the cycling speed, the reduction in energy cost associated with drafting is significantly less with running compared to cycling, but it is still beneficial. Hill (1928) observed that the effect of air resistance when running depended on the air density, the velocity and the projected area of the runner. Pugh (1970) studied the effect of different wind speeds on the running cost. He observed that when the headwind speed increased from 0 $km{\cdot}h^{-1}$ to 16.2 $km{\cdot}h^{-1}$and to 66 $km{\cdot}h^{-1}$, the $\dot{V}O_2$ of a runner running at 15.9 $km{\cdot}h^{-1}$ increased from 2.9 $L{\cdot}min^{-1}$, to 3.1 $L{\cdot}min^{-1}$ and to 5.0 $L{\cdot}min^{-1}$, respectively. Pugh (1971) also observed that at a speed of 6 $m{\cdot}s^{-1}$ (21.6 $km{\cdot}h^{-1}$), running at a distance of 1 meter behind another runner reduced the air resistance by 80%. Drafting is not only beneficial because it reduces the air resistance but also because it reduces the mental effort required to ≪ set and monitor a challenging pace ≫ (Polidori et al., 2020).

Polidori et al. (2020) analyzed Kenesia Bekele's performance at the 2019 Berlin marathon where he won in a time of 2 h 01 min and 41 sec. Bekele used a cooperative drafting strategy and adopted three different drafting positions behind three pacers during the race. Using computational fluid dynamics, they estimated a reduction in metabolic power between 1.9 and 2.8% due to drafting. Furthermore, Schickhofer and Hanson (2021) calculated that the reduction in energy cost when drafting in the best drafting formation possible is 3.5%, which corresponds to an increase in velocity of 2.3% and an improvement in time of 154 seconds for a marathon. Improving the world record IM marathon time by 2 min and 34 sec would still leave a deficit of 6 min and 30 sec compared to the computed theoretical marathon time of 2 h 25 min and 47 sec, thereby highlighting the importance of the cycling portion of the race.

Recommendations

In this section, we will provide recommendations regarding the transition, swim, bike and run course configurations, the organization of drafting as well as for the location of the event and the climatic conditions that would favor the success of the event.

Transition zones, swim, cycling and running courses, and strategies to optimize performance

Transition zones

It is necessary to limit the time lost for the transitioning between sports and therefore the transition area needs to be optimally positioned in relation to the swim and cycling finish line. This objective will be reached by limiting the running time from the swim and bike finish line to the transition zone. Intuitively, this can be achieved by having the transition area to be as close as possible to the swim and bike finish. If the ideal running course is close to the swim course then only a single transition area would be needed. Otherwise, a second transition area, distant from the first, may be required if the running course chosen for the *sub 7 project* is removed from the swim course.

Swim

The swim needs to be in a calm body of water, because waves reduce the swimming velocity by impacting the swimming efficiency (Kjendlie et al., 2018). Furthermore, swimming in the ocean or in a sea is advantageous because of the added buoyancy due to the salt content in the water (Mclean and Hinrichs, 1998). For instance, the two fastest non-current-assisted swimming times in an IM in 2021 (43 min and 28 sec and 43 min and 53 sec) were achieved at IM Cairns, Australia in a calm ocean, with a wetsuit. Also, as mentioned before, swimming in a wetsuit increases velocity. Since the *sub 7 project* would not be eligible as an official world record, a wetsuit could be worn even if the water temperature is higher than 21.9°C. However, swimming in warm water in a full wetsuit increases the risk of hyperthermia, so it is not recommended.

Cycling and Running

The fastest triathlon cycling times have been achieved on moderately flat courses such as at IM Challenge Roth, on highways such as at IM Texas and IM Florida and on race car course such as Formula 1 (F1) and Nascar racetracks (Table 5). These courses are optimal to achieve fast bike splits because they are mostly flat. Hence, less energy is wasted to move a bike uphill against the force of gravity, the quality of the road is good, which minimizes rolling resistance, and they have a small number of turns, with potentially the exception of some F1 courses. Regarding this latter point, turns need to be limited such to minimize the amount of kinetic energy lost by breaking or coasting before a turn. Furthermore, turns can be difficult to navigate in a group.

For the current IM world cycling record achieved during the ZTBR, a cycling ramp, similar to a velodrome ramp, was built to allow the triathletes to make a 180° turn without having to slow down. This technology could be used for the *sub 7 project* if it were to occur on an out-and-back course such as a highway. However, since the *sub 7 project* will most likely occur with the help of pacers it would be important to practice riding the velodrome-like ramp in a group to minimize the risks of crashes during the attempt.

With respect to the run course, it must also be flat and not have any sharp turns, since elevation gain increases the metabolic cost and curves require the runners to generate additional centripetal force on the ground with their legs, which also increases the metabolic cost (Taboga and Kram, 2019; Snyder et al., 2021).

Meteorological conditions

A significant amount of body heat is produced (Longman et al., 2021) during exercise due to the conversion of chemical energy into mechanical energy, which is a highly inefficient process. The amount of body heat produced is proportional to the exercise intensity. On the other hand, the capacity of the body to dissipate heat to the environment is inversely proportional to the water pressure in the air surrounding the skin and directly proportional to the temperature gradient between the skin and the environment. It is important to limit the gain in body heat during exercise as it may lead to premature fatigue and impair performance (Cheuvront et al., 2010). Hence, the choice of the location and the time of the year for the *sub 7 project* is crucial; the temperature should neither be too warm nor too cold and the relative humidity should ideally be as low as possible. Solar load also would need to be as low as possible to minimize body heat gain, unless the race is being conducted in relatively cool weather.

Knechtle et al. (2019) analyzed the Boston marathon performances from 1972 to 2018 and observed that for every increase of 1°C in the average temperature, the winners' finishing times increased by 20 seconds and the average finishing time of all the finishers increased by 1 min and 47 sec. It is well documented that the optimal temperature for a marathon performance is between 10 and 12°C (El Helou et al., 2012; El Helou et al., 2007) or between 8 and 15°C (Suping et al., 1992). For instance, the location and the time of day and year for the *INEOS 1:59 challenge* were chosen so that the runners could run at a temperature of about 10°C (INEOS 1:59 Challenge, n.d.).

For running performance, the temperature must be low since the effect of convection is minimal due to the relatively slow speed of the runners. However, when cycling, the cooling effect of the wind is significantly more important. Therefore, a temperature of 10 °C may be too cold while cycling, and the racing triathlete would need to stop at the first transition to add some clothes and energy may be lost due to thermogenesis. Therefore, a delicate balance between the ideal temperature for cycling and running should be taken into account. However, a possible scenario could be to choose a region where the IM would start after noon when the temperature is in the low 20°C or slightly lower and the radiative effect of the sun is high, so that the racing triathlete could begin the marathon at sunset when both the temperature and the solar radiation are declining.

Altitude

For every 305 m increase in altitude, there is an ∼3% reduction in air density (Levine et al., 2008). Therefore, when cycling at altitude, cyclists encounter less air resistance, which results in an improved performance, unless the physiological detriment associated with the altitude is higher than the improvement associated with the reduction in aerodynamic drag (Capelli and di Prampero, 1995; Bassett, 2000; di Prampero, 2000; Padilla et al., 2000; Hahn and Gore, 2001; Atkinson et al., 2003; Heil, 2005). For instance, both the hour record and the 4000 m cycling records were achieved at the Aguascalientes velodrome in Mexico, which is at an altitude of 1800 m (Delaney, 2021; UCI., 2021).

It would therefore be tempting for organizers to consider having the *sub 7* project at altitude. However, altitude is associated with a decrease in performance for aerobic activities due to a decrease in $\dot{V}O_{2max}$ and an increase in the relative intensity at any speed or power output (Garvican-Lewis et al., 2014, 2015; Burtscher et al., 2018). Furthermore, since the effect of air resistance while running a marathon is low, the reduction in air density whilst running at altitude is not beneficial since the physiological impairment is considerable.

Time of year and location

As previously mentioned, the bike and run courses must be flat, the swim must be in a calm body of water and ideally in salt water and the temperature and humidity must be low, but manageable on the bike without the addition of clothing. One ideal location would be Bahrain, which is where the half-IM world record was broken. The swim would occur at the Bahrain bay which is a calm body of salt water. The bike and run courses would be flat and have a small number of turns. The ideal time of year would be January; it is the coldest month of the year in Bahrain with average temperature ranging between 14.7 and 20°C, the water temperature is about 19.8°C (Weather-Atlas, n.d), rain is sporadic, solar radiation is significantly lower in January (4.8 kWh/m^2 day compared to over 6.5 kWh/m^2 day in the summer months) (Alnaser et al., 2014) and sunset occurs at about 5 PM. Therefore, the IM could begin at 13h00 so to have the run start when both the temperature and solar radiation are lower.

Organization of drafting

The way drafting will be structured for each of the three sports must be carefully planned and orchestrated for it to provide the best results possible. For the swim, there are two possible positions where a swimmer can be situated to benefit from the draft of other swimmers. One option is to swim between 0 to 50 cm behind the toes of the lead swimmers. The other position, called lateral drafting, requires the swimmer to be located 50 to 100 cm back from the hands of the lead swimmer. However, swimming at the feet is more advantageous (Chatard and Wilson, 2003). In order to maximize the reduction of hydrodynamic drag, the racing triathlete should swim behind five pacers positioned in an arrowhead position (Figure 3A).

For the cycling, based on Blocken et al. (2018)'s study, the optimal situation would be to have 6 lead cyclists in front of the racing triathlete and to try to maintain a space of 5 to 15 cm between each cyclist (Figure 3B). The utilization of radio communication is recommended so that the race organizers and coaches can communicate with the lead cyclists and the racing triathlete. The 6 lead cyclists would need to rotate in order to share the lead and therefore spend short period of times at the front where the aerodynamic drag is the greatest (Shirasaki et al., 2017). They could be replaced by other cyclists at the half point of the 180 km to make sure that the racing triathlete has 6 fresh lead cyclists throughout the entire cycling distance.

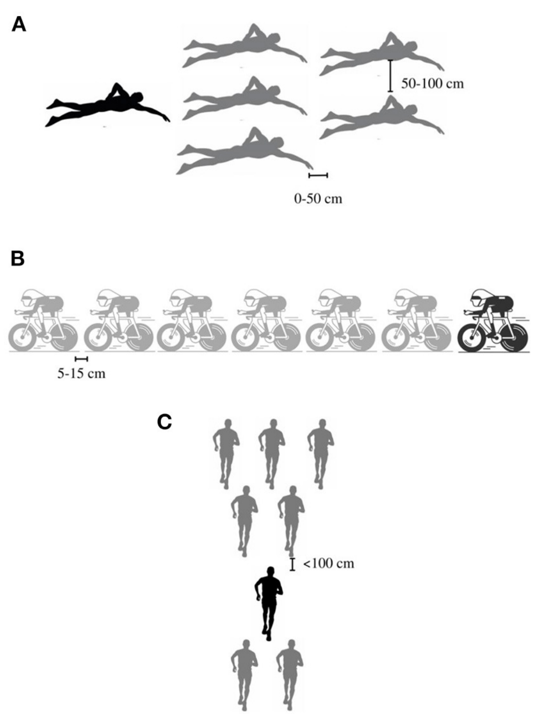

FIGURE 3
Recommended drafting organizations for **(A)** Swimming, **(B)** Cycling and **(C)** Running. The blackest drawings represent the racing triathlete.

Motorcycles could be used to provide on-course food and fluid to the athletes. As a result, instead of having to slow down and get out of his aerodynamic position on his bicycle to grab bottles or gels from an aid station, the racing triathlete would be able to maintain his aerodynamic position and speed, which would allow him to save time and energy. The feeding for the pacers should occur as the lead pacer finishes his pull at the front of the group so that he can coast at the end of the group and receive food and fluids without putting the other cyclists at risk.

For the run, a drafting organization similar to the one used for the sub 2-h marathon attempts is recommended (Figure 3C). For the first sub 2-h marathon attempt, it was decided to have new pacers after every lap of 2.4 km. Kipchoge was running behind another runner who was preceded by 6 runners who were forming an arrowhead. For the second attempt at breaking the 2-h mark, 7 pacers were used, but this time 5 pacers were running in front of Kipchoge in an inverted arrow-head formation and 2 pacers were running behind him (Polidori et al., 2020). For the *sub 7 project*, 7 pacers should be used, and in order to make sure that they can sustain that pace, 7 new pacers would replace them at the half-marathon mark. People riding electric bicycles could ride alongside the runners to provide food, liquids and verbal encouragement.

Discussion

We determined, based on the trends of the improvement of the IM times over the years, that a sub 7-h IM is unlikely to be achieved without any external assistance. However, this prediction is based solely on trends, so it is not impossible that a sub 7-h IM without any external assistance could be achieved in the future thanks to sophisticated training programs and better monitoring of the recovery process. The arrival of new technologies could also be a game changer. For instance, the use of 3D printing in the development of time trial handlebars with the goal of improving aerodynamism could be extended to create custom, wind-cheating bicycles (Croxton, 2021). Although a taboo topic, it cannot be ruled out that performance-enhancing drugs could be used without being detected, either because of micro-dosing strategies or because the active compound has not been yet been identified by researchers (Joyner et al., 2020). Furthermore, over the past few years, triathletes have begun to compete in IM races at an earlier age which may provide them with more time to improve at that distance while there are still at their peak fitness level.

In this article, courses with a significant negative elevation and with a current-assisted swim were not considered because they fell outside our definition of external assistance. However, a current-assisted swim could help reduce the overall time by as much as 8 min.[7] Also, a sub 7-h IM could possibly be achieved by swimming in a lake at altitude and then immediately cycling down to a town at low altitude, where the racing athletes would complete their cycling ride. The descent to a lower altitude would allow triathletes to save precious time and energy and enable them to start the run on a fresher body and mind.

The *sub 7 project*, similarly to the *sub2* marathon projects, would require a lot of organization, planning and substantial funding. Furthermore, it would also require a strong commitment in time from the organizers, the pacers and the racing triathlete involved in this event. The triathlete must fully commit to this event, so it should not occur during an Olympic year. Furthermore, he would need to train specifically for this event for many months and to practice the pacing and drafting strategies with the pacers to optimize efficiency and reduce the risks of crashes, especially while cycling. Finally, this achievement would need to be executed, of course, in an ideal location and, most importantly, under perfect meteorological conditions. Therefore, it is recommended to not have the race planned on a fixed day, but rather to plan the race to occur within a spectrum of days ranging from 3 to 5, for instance. Therefore, a careful coordination between race organizers and local authorities and planning of training, diet and hydration for

7 This reduction in time is estimated by comparing the current-assisted swim time to non-current-assisted swim times.

the racing triathlete in the days leading to the race, and within the targeted possible racing days, if need be, would be required.

In conclusion, a sub 7-h IM would be a significant sporting achievement similar to the first sub 4 min mile and the first sub 2-h marathon and physical, psychological and technological boundaries would need to be broken.

Author contributions

AJD conceived the idea of this article and did research on this topic with the supervision of EDBG. EDBG and AJD performed the analysis of the Ironman^{TM} times. AJD wrote the first draft. EDBG provided guidance on how to present the results, revised the final versions of the manuscript, and the general concepts of this manuscript. All authors discussed the results and contributed equally to 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.

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Recommendations for the design of randomized controlled trials in strength and conditioning. Common design and data interpretation

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Introduction

A central aim of strength and conditioning (S&C) coaches is to improve their athletes' performance with exercise prescription (The team physician strength conditioning of athletes for sports: a consensus statement, 2015). Coaches select specific exercises because they have previously had positive experiences with such exercises and because of existing scientific evidence supporting the validity and efficacy of those exercises (Murad et al., 2016; Wackerhage and Schoenfeld, 2021). Research in S&C has drastically increased over the last 20 years, leading to many modern-day practitioners basing their exercise prescription on the most advanced and updated scientific evidence. Therefore, research in S&C plays a key role in the design, implementation, and variation of training protocols (Beato et al., 2021). Sports practitioners, as seen in the field of medicine, have embraced the use of evidence-based practice to improve the likelihood of success (achieving their planned aims) of their training prospection (Wackerhage and Schoenfeld, 2021). However, sport science is plagued by popular beliefs, myths and poor-quality evidence (Gabbett and Blanch, 2019). There are many reasons why the quality of articles is sometimes low, for example, the authors' knowledge of research methods or statistics is inadequate (Cleather et al., 2021; Sainani et al., 2021), the resources invested in the research are limited, or the research was carried out in a hurry, which could be related to many reasons, for instance, several studies are performed by students who have limited time and experience when performing data recording (Abt et al., 2022). Consequently, a key question remains: what should we do to improve current scientific evidence and limit the spread of new low-quality evidence? While it is assumed that not all published articles are of high quality and that in some cases there may be errors (Sainani et al., 2021), this should not be common (Smith, 2006). Consequently, the objective of this article is to make some recommendations in the field of research design, specifically, randomized controlled trials (RCTs) and data interpretation, with the aim of improving the robustness of future S&C research (e.g., training, performance, injury prevention) and avoiding the replication of common mistakes.

Evidence pyramid

S&C prescription should be based on the most relevant and updated scientific evidence, as reported above, following where possible an evidence-based approach (Murad et al., 2016; Wackerhage and Schoenfeld, 2021). Researchers and practitioners who design training protocols should be aware of the evidence pyramid (Murad et al., 2016), where evidence is categorized based on robustness (derived from study type). At the bottom of the pyramid, we find experts' opinions and case reports, while at the top we find meta-analyses and systematic reviews, followed by (a level lower) RCTs. Practitioners should design their training protocols using the evidence on the top of this pyramid and if such evidence is missing, they can use the less robust articles up to the last level. If there is no solid evidence, expert opinions can be useful. However, such opinions should be considered for what they are and should not be assumed as true – in particular when they are based on unpublished data or on exclusively personal arguments. Despite this, researchers and coaches should work together to verify the validity and effectiveness of strategies that coaches are already using based on their experience gained with athletes.

In the field of S&C, which is the main focus of this article, we are well aware that some of the most common limitations are the length of interventions (frequently too short) (Rothwell, 2006), a low number of participants enrolled (the calculation of the sample power is also frequently missing), and the lack of a control group in the study design (Moher et al., 2001). With such limitations in mind, the effect of the intervention is often influenced by other factors not associated with the protocol that can undermine the evidence's robustness. Therefore, it is important that researchers avoid these errors and increase the robustness of their intervention studies [also embracing open-science (Calin-Jageman and Cumming, 2019)] to provide stronger evidence to practitioners, who can apply such evidence later in their daily practice.

Recommendations for the design of RCTs

There is the need for more robust evidence and the design of RCTs (following CONSORT guidelines) (Moher et al., 2001) should be a priority for researchers in the S&C field in order to verify training interventions. Researchers and practitioners can find some recommendations for the design of RCTs in the following lines (see Table 1).

Conducting all four phases of RCTs

To enhance our research design knowledge, researchers in S&C could learn something from clinical medicine (Atkinson et al., 2008). Clinical trials are classified into phases based on the objectives of the trial. Phase 1 trials are the first studies that verify the effect of an intervention and are usually carried out involving small samples (e.g., larger single-group or controlled study) (Evans, 2010), phase 2 trials involve a larger sample (e.g., RCTs) and aim to understand, for instance, the efficacy of an intervention vs. a control or the dose-response relationship, phase 3 trials should aim to confirm the efficacy of an intervention using a larger sample (e.g., collaboration between research groups), while phase 4 trials are "confirmatory or registration" trials (Atkinson et al., 2008; Evans, 2010). If we try to transfer what has just been said to S&C, despite the differences between medicine/clinic and sport, we can understand that the size of the selected sample of a trial (and phase) should be based on the existing level of knowledge on the subject. Therefore, if a new training method is to be studied, small sample sizes may be adequate, but if this training method has already been proven effective, it would not be adequate to continue to carry out small studies, instead future trials should involve large samples (e.g., evaluating dose-response relationship).

Sport scientists could consider the design of a framework of this type in the future; however, it is not suggested here that sport scientists must label their trials in phases. Instead, this study recommended to design small-sample studies when weak evidence exists (subsequently, these studies can be combined in a meta-analysis), but to avoid designing many of them where some robust evidence already exists and to increase the sample size of their studies to answer different research questions, for instance, confirm the efficacy of an intervention with a lower training dose or compare different interventions (e.g., superiority trials).

Practitioners and researchers should also be aware of practical problems associated with the design of RCTs. RCTs are sometimes impractical in sport research for various reasons such as not enough athletes in the elite team to split into two groups, unwillingness of the coach to have a parallel control group, and logistical difficulties with having two kinds of training. In this case, other designs (e.g., repeated-measures) aimed at overcoming these problems can be a valid alternative (Vandenbogaerde et al., 2012), although they have a lower position (therefore robustness) in the evidence pyramid.

Randomization

RCTs are studies that aim to verify a research hypothesis in which a number of participants (e.g., athletes) are randomly assigned to some groups that correspond to some specific training protocols. A simple example of an RCT could be the comparison between an innovative resistance training method vs. a control group or an active control based on the existing knowledge (current best-practice treatment as control). To successfully verify that this innovative

TABLE 1 Summary of the recommendations for the design of randomized controlled trials and data interpretation in strength and conditioning.

Evidence pyramid	Recommendations for the design of RCTs	Errors and sample size	Other considerations
The central aim of S&C coaches is to improve their athletes' performance with exercise prescription. S&C prescription should be based on the most relevant and updated scientific evidence following where possible an evidence-based approach.	Following CONSORT guidelines and learn from clinical medicine (see phases of RCTs). Sport science practitioners should design small-sample studies when weak evidence exists, but to avoid designing many of them where some robust evidence already exists and to increase the sample size of their studies to answer different research questions.	Type I error: a training method is found effective when it is actually ineffective (false positive). Type II error: a training method is found ineffective when it is actually effective (false negative).	A common statistical error is the use of within-group comparisons instead of between-group comparisons to determine longitudinal differences between interventions. The experimental and control groups must be directly compared.
Evidence pyramid categorized evidence based on robustness. At the top of the pyramid, we find meta-analyses and systematic reviews, followed by (a level lower) RCTs, while at the bottom we find experts' opinions and case reports.	Researchers need to control for bias and confounding factors. Researchers and practitioners can use different types of randomization such as simple, block, stratified, unequal randomization, and covariate adaptive randomization.	Inadequate sample size: small samples, first, increase the chance of making a type II error, second such underpowered studies could struggle to find difference between interventions (or a control group) spreading wrong evidence, third they could be a waste of time and money for researchers and athletes.	This paper uses null hypothesis significance testing for assessing differences between interventions, but significance testing/*p*-values answer a very narrow question and should never be the sole focus.
Practitioners should design their training protocols using the evidence on the top of this pyramid and if such evidence is missing, they can use the less robust articles up to the last level.	Practitioners should be aware of the differences that exist between designs such as RCTs, superiority and non-inferiority trials, and they should select the most adequate research design based on the existing evidence reported in the literature.	Practitioners should be aware that the sample size matters, and adequately powered studies should be prioritized because they offer more robust evidence. Practitioners could use G*Power to calculate the statistical power of their studies (Figure 1).	*P*-values are often used dichotomously (yes or no decision-making process). Researchers also need to consider the effect sizes and CIs.
Common limitations in the field of S&C are the length of interventions (too short), a low number of participants enrolled, and the lack of a control group in the study design.	Control group: Researchers can involve a traditional control group (no-intervention group), or they can compare the effect of a new intervention vs. active control, specifically, an intervention which has been proven to be effective (e.g., current best-practice treatment).	CIs are related to the selection of the alpha value, CIs = (1 - alpha value)*100%. Therefore, an alpha value of 5% corresponds to a 95% CIs. Using 90% CIs is possible, but this decision should be justified because using it increases the risk of Type I error.	CIs provide critical information beyond statistical significance such as they provide a plausible range of values for the true effect and reveal the precision of the estimate.

RCTs, Randomized controlled trials; S&C, Strength and conditioning; CONSORT, Consolidated Standards of Reporting Trials; CIs, Confidence intervals.

resistance training method is effective (alternative hypothesis) (Calin-Jageman and Cumming, 2019), researchers need to control for bias and confounding factors (Evans, 2010). Randomization is a way to control for such factors, therefore, the participants of the groups should be randomly allocated into these groups and not arbitrarily selected by the researchers (or coaches). In such a case, we should speak about a non-randomized controlled trial, which is a different study design with lower robustness (Sedgwick, 2014). Researchers and practitioners can use different types of randomization such as simple, block, stratified, unequal randomization (a smaller randomization ratio such as a ratio of 2:1), and covariate adaptive randomization (Suresh, 2011).

Control group and active control

A key step for the robustness of an RCT is the selection of a control group. A control group, in particular for phase 1 and 2 studies, should avoid performing any relevant training protocol which could affect the validity of the trial. It is clear that if researchers do not know the efficacy of a new training method, they need to verify its effect vs. a control group. When some RCTs with these characteristics have been successfully performed, researchers could state that this new method is effective (if enough RCTs are available, a meta-analysis could be performed) (Liberati et al., 2009). In sport and medicine there is an alternative to RCTs using a no-intervention control group, that is a trial that involves an active control. This situation is very frequent in sport because many training methods are known to be effective, therefore designing trials with a no-intervention group (as control) that involve athletes is sometimes impractical or considered unethical. In this case, the researchers do not involve a no-intervention group, but they compare the effect of a new intervention vs. an intervention which has been proven to be effective (e.g., current best-practice treatment). In clinic, this approach is used when a standard of care treatment already exists, therefore the new treatment should be tested against it and, for example, proven to be superior (i.e., superiority trials or non-inferiority trials) (Schiller et al., 2012).

Considering what was reported above, researchers in S&C should be aware of the differences that exist between trials of different phases and between designs such as RCTs, superiority and non-inferiority trials, and they should select the most adequate research design (to answer their research question) based on the existing evidence reported in the literature.

Common mistakes that we can find in RCTs

Some of the common mistakes that can be found in RCTs are: the selection of inadequate sample size, the use of an inadequate alpha level, the use of flawed statistical methods, and the wrong interpretation of the results of the study.

Inadequate sample size

The use of inadequate sample size is a limitation that has been reported in several methodological papers and it should not surprise anyone with research experience (Sainani and Chamari, 2022), however, the design of underpowered studies is still very common in S&C (Beck, 2013). Researchers and practitioners should be aware that small samples, first, increase the chance of making a type II error, which means that a training method is found ineffective when it is actually effective (false negative) (Evans, 2010), second such underpowered studies could struggle to find difference between interventions (or a control group) spreading wrong evidence, third they could be a waste of time and money for researchers and athletes (Atkinson and Nevill, 2001a). Therefore, practitioners and researchers should be aware that the sample size matters, and adequately powered studies should be prioritized because they offer more robust evidence. Researchers and practitioners could use G*Power (which is a free-to-use software) to calculate the statistical power of their studies (as reported in the example in Figure 1). Further information about G*Power can be found here: https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower.

Type I error and confidence intervals

Type II error is an issue; however, it is more "dangerous" to design intervention studies using an unsuitable alpha level, which can lead to the claim that an intervention is effective when it is not (false positive) (Evans, 2010). In S&C as well as in clinic (or medicine) the most common alpha level is 5% ($p = 0.05$) (Peterson and Foley, 2021). CIs are related to the selection of the alpha value, CIs = [1 - alpha value]*100% (Chow and Zheng, 2019), therefore an alpha value of 5% corresponds to a 95% CIs. Researchers in S&C should be well-aware of the differences of using either 95% CIs or 90% CIs because the type I error would be affected. Previous researchers reported that it is unethical to use lower alpha (or a one-tailed test) just to show that a difference is significant, and therefore the decision on the use of 90% CIs should be justified (in advance, e.g., pre-registration) (Atkinson and Nevill, 2001b). It is important to clarify that researchers can use the alpha level they considered more suitable for their research if this is properly justified but they should not use 90% CIs as default (it increases risk of false positive). A clear example of this issue is reported by Diong (2019) in a letter to the editor related to the paper published by Pamboris et al. (2019), where is reported that the use of a 90%CIs are more likely to report an effect that does not exist (type I error). A final consideration concerns the use of a one-tailed test, which has more probability to find a difference between the groups (e.g., intervention vs. control), but this test should be used if the researchers want to determine if there is a significant difference in one direction, while there is no interest in verifying if a difference in the other direction exists.

Data interpretation and statistical methods

Another important issue is the use of flawed statistical methods; one example in sport science is the use of magnitude-based inference (or magnitude-based decision analyses), which is a controversial statistical approach that has never been adopted by the statistical community (Sainani, 2018; Sainani et al., 2019). Although this approach has been used in hundreds of papers in sport science, it has been repeatedly been demonstrated as unsound and it should not be used in S&C (or sport science) research (Sainani, 2018; Lohse et al., 2020). Magnitude-based inference reduces the type II error rate (false negative) but with the tradeoff is a much higher type I error rate (Sainani, 2018). This method has also been labeled as Bayesian,

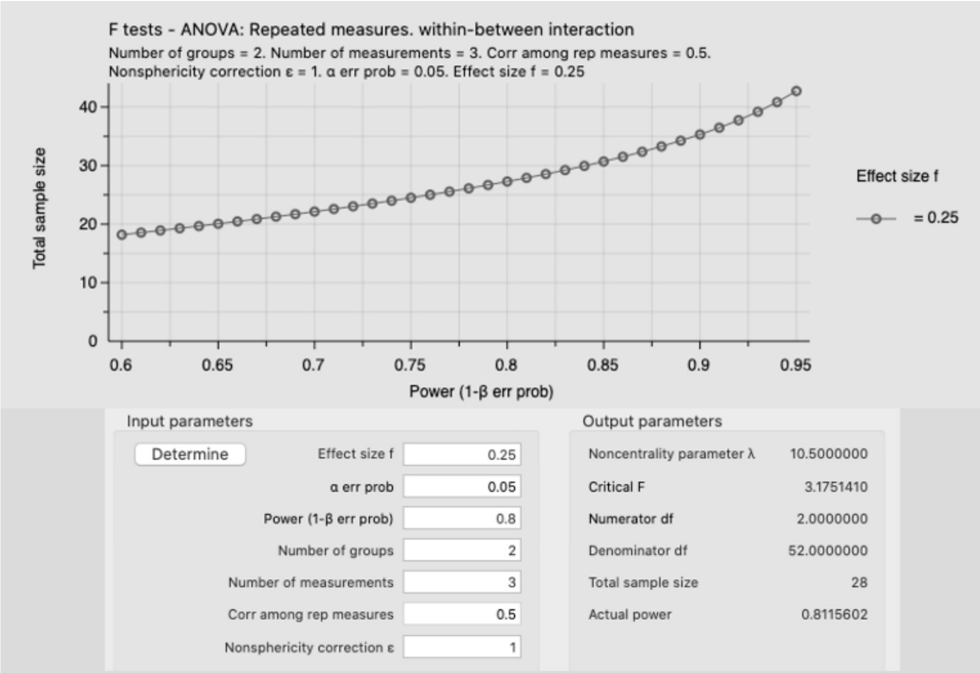

FIGURE 1
Example of an a priori power analysis using an ANOVA, repeated measures, within-between interaction with a *medium* effect size (f = 0.25) and an alpha error prob of 0.05 (5%). The total sample size for this study is 28 participants, with an actual power of 0.811. Moreover, this figure shows that increasing the sample size (y axis) is possible to increase the power (1-beta err prob), for instance, recruiting 35 participants would increase the sample power to 0.9, which would decrease the type II error.

but it is not universally accepted to actually be Bayesian (Welsh and Knight, 2015).

This paper uses null hypothesis significance testing for assessing differences between interventions; however, significance testing/ *p*-values answer a very narrow question, *p*-values are often used dichotomously (yes or no decision-making process, e.g., $p = 0.049$ or $p = 0.051$, respectively) (Betensky, 2019), therefore, they should never be the sole focus; researchers also need to consider the effect sizes and CIs.

Between-group and within-group comparisons

Another common statistical error is the use of within-group comparisons instead of between-group comparisons to determine longitudinal differences between interventions. Many researchers (or practitioners) conclude that an intervention is successful if there is a significant within-group difference in the experimental group but not in the control group or if the effect size of the experimental group is larger than the effect size of the control group. However, this is not the correct comparison (Nieuwenhuis et al., 2011)–the experimental and control groups must be directly compared, for instance with ANOVA or ANCOVA.

Interpretation of the results based on confidence intervals–when it does cross zero

It is common to find papers that use CIs to make decisions but interpret them incorrectly. Since there is a one-to-one-correspondence between CIs and *p*-values (as explained above), this means that if the CI about a between-group mean difference (e.g., in an RCT) does not cross zero, there is a statistically significant difference between the intervention and the control group, while if the CI does cross zero, it means that there is no significant difference between groups at the specific alpha value selected (e.g., 5% that corresponds to 95% CIs). However, there are still cases where researchers wrongly interpret CIs (Diong, 2019; Mansournia and Altman, 2019). For instance, in this paper (Pamboris et al., 2019), some CIs of between-condition comparisons crossed zero, meaning that there is not a statistically significant difference between conditions, yet the authors still claimed to find a difference (as subsequently explained in this letter, Diong, 2019). Importantly, CIs provide critical information beyond statistical significance such as they provide a plausible range of values for the true effect and reveal the precision of the estimate (Sainani, 2011).

Conclusion

This paper aimed to make some recommendations in the field of research design and data interpretation with the aim of improving the robustness of future S&C research and avoiding the replication of common mistakes that can be found in the sports literature. Much can be learned from the clinical field therefore practitioners, coaches and researchers should be encouraged to adopt research methods coming from such research area when they design RCTs. In S&C there is the need for more robust RCTs which should have longer duration, greater number of participants enrolled, and the right type of control group (no-intervention control or active control) based on the existing knowledge. Finally, researchers should be aware of some common mistakes that should be avoided such as the selection of a sample of inadequate dimension (type II errors) or inadequate alpha levels (risk of type I), the use of flawed statistical methods, and the incorrect selection of a statistical test or the wrong interpretation of CIs of their study.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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Conflict of interest

The author declares 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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Pre-season body composition has minimal influence on in-season match availability, and match performance in female Australian Football League (AFLW) players

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This study examined the relationship between pre-season body composition, in-season match performance, and match availability in female players competing in the Australian Football League Women's (AFLW) competition. With the outlawing of body composition assessments as part of pre-draft player evaluations in the AFLW, this study seeks to examine whether this is justified. Twenty-two ($n = 22$) players had body composition assessed with dual-energy x-ray absorptiometry at the beginning of the 2021 AFLW pre-season (whole-body and regional fat mass and lean soft-tissue mass [LSTM]). In-season match availability and match performance data (Coaches Score [CS], Champion Data Player Rank, average disposals, disposal and kicking efficiency) were collected throughout the 2021 competition. Pearson correlations were performed to assess if associations existed between body composition and in-season match performance and availability. A median split was performed to divide players into higher and lower performing groups for match performance variables. Two-sample independent *t*-tests were then used to assess differences between groups. No body composition characteristics could differentiate between in-season match availability groups (100% availability vs. <100% availability) or higher and lower performing groups for all match performance variables. Total leg LSTM asymmetry shared a moderate negative association with CS. Body composition may not be important for determining in-season match availability and performance in female AFLW players. Thus, the repercussions following the removal of pre-draft body composition assessments across the league may not be as significant as is currently perceived. Other physiological, biomechanical, or performance qualities are more variable and may mask the effect of body composition in these players. AFLW practitioners should prioritize the development of other important attributes, such as aerobic fitness, muscular strength and power, and technical skill.

KEYWORDS

anthropometric, injury, prevention, physiology, symmetry, muscle, skinfolds, testing

Introduction

The elite Australian Football (AF) league for females was established in 2017 (Australian Football League Women's [AFLW]) with eight teams competing. However, over the last few years, the league has rapidly expanded, and now features 18 teams. Running demands in the AFLW have been documented over the last several years (1, 2) with similar relative running intensities (distance/minute) observed with the AFL (3, 4). However, AFLW has been observed to be a tighter, more crowded game, with a greater number of tackles, errors and contested possessions observed per minute of match play compared with the AFL (5). This may help explain the differences in injury epidemiology between the two competitions with AFLW players seven times more likely to sustain an ACL injury than AFL players (6, 7) and AFLW players experiencing a greater proportion of contact injuries (8, 9). Conversely, the incidence of hamstring injuries in AFLW players are only a quarter of that of AFL players which may be due to the lower quantity of high-speed running that AFLW players undertake (2, 3). Thus, it could be suggested that the elite women's game requires different technical and physical attributes than the elite men's game.

Mitigating injury, increasing player availability, and maximizing physical performance throughout a competitive season is a key responsibility of high-performance staff. Whilst body composition characteristics have been linked with injury and physical performance in AFL players previously (10), no such association has been established with elite female AF players. Large differences in body composition characteristics have been observed between elite male and female AF players (11) which is likely due to differences in sex hormones (12), vast differences in physical match demands (4) and increased reliance on fats as an energy fuel source in females (13). Additionally, large variations in body composition characteristics have been observed for female AF players across the developmental pathway (14). Specific body composition characteristics are considered vital for physical performance as muscle mass contributes to force production, and fat mass (FM) is known to hinder thermoregulation and general locomotion (15). However, higher levels of FM may be advantageous in some sports, such as those with high in-game congestion, where contacts and collisions are a regular occurrence and total body weight is less problematic, such as the rugby codes (rugby union and rugby league).

Recently however, the AFL announced that body composition testing (*via* skinfolds) will be removed from all future pre-draft assessments across the elite men's and women's competitions (AFL and AFLW) (16). While this has been mandated by the AFL organization to reduce the psychological stigma and possible ramifications surrounding perceived body image (16), many clubs have expressed disappointment about the inaccessibility of this information until after a player has been drafted and signed despite its clear implications toward physical preparedness. Subsequently, greater insight into the importance of body composition data, particularly among female AFLW players, is crucial in understanding whether the removal of these assessments will impact future performance or match availability. Thus, the purpose of this study was to examine whether body composition characteristics were associated with on-field match performance, and in-season match availability in female players competing in the AFLW. We hypothesize that greater muscle mass and body mass will be associated with higher match availability with lower relative fat mass being associated with greater match performance.

Materials and methods

Study design

An observational PROSPECTIVE cohort study was used. Body composition data was obtained at the beginning of pre-season for a cohort of elite female AF players in the lead-up to the 2021 AFLW season. Pre-season training lasted for 3 months and consisted of three main training sessions per week of ~2 h in duration (resulting in ~20 kilometers (km) of total weekly running distance), two full-body resistance training sessions and individual extras (recovery, yoga, Pilates, cross-training). Match availability and match performance data were collected prospectively throughout the 2021 AFLW season. An in-season week consisted of one competitive match on the weekend, two main training sessions (~9–10 km total weekly distance) and two resistance training sessions which prioritized upper body earlier in the week and lower body at the end of the week.

Subjects

Twenty-four elite female AF players (mean ± SD; age = 25.8 ± 4.4 years; playing experience = 3.0 ± 1.5 years; height

= 169.8 ± 6.7 cm; body mass = 66.0 ± 6.7 kg) from one AFLW club participated in this study. To be eligible, players needed to be injury-free at the beginning of the competitive season (late January). This ruled two players out of the study who sustained injuries in the pre-season and missed the entire season. These players were subsequently removed from analysis. This left 22 AFLW players in the study (Table 1). Written informed consent was provided by the participating AFL club, outlining the arrangement with players to have their data collected as part of their contractual agreements for use in club operation and research endeavors. Ethics approval was provided by Edith Cowan University's Human Research Ethics Committee (ID: 2020-01055).

Anthropometry

Height and body mass were acquired prior to undertaking the body composition assessments. Stature was recorded to the nearest 0.1 centimeter (cm) using a free-standing stadiometer (Model 217, Seca, Hamburg, Germany) with body mass measured on a calibrated weight scale (Model 22089, Seca, Hamburg, Germany).

Body composition

Body composition was assessed using fan-beam whole-body dual-energy x-ray absorptiometry (DXA; Hologic, Horizon A, Danbury, CT, USA). Whole-body scan procedures were followed in accordance with previous work by our research team (17). Players were instructed to avoid any moderate to vigorous exercise in the 24 h prior to their scan, have emptied their bladder and arrive in a euhydrated state. All players wore their club-issued training singlet and shorts with all jewelery and metallic items removed. All whole-body data were reported with the removal of the head (WBLH; whole body less head) to maintain consistency throughout the cohort. The same qualified technician (CJM) conducted all scans and subsequent analyses. The machine was calibrated daily in accordance with manufacturer guidelines. Post-scan analysis involved the adjustment of anatomical lines to separate the various body regions including the arms, torso, and legs. The upper body (UB) was defined as everything above the iliac crest of the pelvis (excluding the head). The lower body (LB) consisted of both legs, from the feet to the femoral neck. Further sub-regions were created for the right thigh, left thigh, right shank, and left shank in accordance with our previous work (18). The coefficient of variation for the operator using the same machine in the same facility was between 0.22 and 5.09% for whole-body (total mass = 0.22%; lean soft-tissue mass (LSTM) = 0.41%; fat mass (FM) = 1.61%) and sub-regional measures (Leg LSTM = 0.95%; Leg FM = 2.36%; Thigh LSTM = 1.02%; Thigh FM = 2.27%; Shank LSTM = 1.73%; Shank FM = 5.09%). WBLH FM and LSTM were obtained along with FM and LSTM for all the sub-regions. In this study, LSTM included all fat-free soft-tissue mass and is used as a surrogate measure for muscle mass.

Match availability

For every game in the 2021 season, the strength and conditioning specialist, physiotherapist and medical doctor collectively, would categorize each player as 'available' or 'unavailable'. A player was deemed available if the coaching group were able to select them, regardless of whether they played in the AFLW or the Western Australian women's state league (WAFLW) for that given week. As there are 30 contracted players on an AFLW list and only 21 players selected to play in the AFLW for a given week, some players may be required to play in the state (reserves) competition. A player was deemed unavailable if they could not be selected to play due to injury, illness, suspension, or personal reasons. No player in this study missed a game due to suspension, illness or personal reasons and were only deemed unavailable through injury.

Match performance

Coaches' score

Coaches' Score (CS) are a subjective measure of match performance. The senior coach, line coaches collectively (forwards coach, midfield coach and backline coach) and the head of women's football would rate each player's performance on a scale of 0–3 (0 = poor performance and limited impact on game; 1 = played role to standard; 2 = played above expectations, good performance; 3 = exceptional performance with high impact on game). Thus, each player could receive a maximum score of 9 in a game if awarded a score of 3 by each party. Players' match performance was not rated in games in which they sustained an injury. The scale used was chosen by the club. CS have been presented as an average score received per game played.

Champion data player rank

Champion Data © Player Rank (CDPR) was used as an independent, and objective measure of match performance and is based on official statistics that players accumulate during a match (Champion Data ©, Melbourne, Australia). CDPR is a value based on an algorithm which considers a wide array of in-game statistics and has been developed to rate player performance and is widely accepted within the AF industry (19). The statistics that are part of the CDPR algorithm are collected in real-time by trained professionals. Slight adjustments may be required by watching a replay of the game in-depth afterwards.

TABLE 1 Body composition and match performance (mean ± SD) data of all AFLW players and those within each in-season availability group.

	All players (*n* = 22)		<100% availability (*n* = 12)		100% availability (*n* = 10)	
Descriptives						
Age (y)	25.8 ± 4.4		26.5 ± 4.6		24.9 ± 4.2	
Height (cm)	169.8 ± 6.7		171.0 ± 6.4		168.4 ± 7.2	
Body mass (kg)	66.0 ± 6.7		65.9 ± 7.0		66.1 ± 6.8	
Playing experience (y)	3.0 ± 1.5		3.2 ± 1.7		2.8 ±1.4	
In-season match performance and availability						
Average coaches score	1.9 (2.5)		1.7 (3.4)		1.9 (2.0)	
Average champion data player rank	66 ± 22		62 ± 22		72 ± 22	
Average disposals	9.0 ± 3.5		7.8 ± 3.7		10.4 ± 2.9	
Kicking efficiency %	47.9 ± 12.1		48.1 ± 10.3		47.8 ± 14.4	
Disposal efficiency %	59.0 ± 9.0		60.3 ± 8.6		57.7 ± 9.7	
In-season match availability %	94.4 (22.0)		77.8 (11.0)*		100.0 (0.0)	
Body composition characteristics						
	Absolute (kg)	**Relative (%)**	**Absolute (kg)**	**Relative (%)**	**Absolute (kg)**	**Relative (%)**
WBLH LSTM	47.6 ± 4.4	76.2 ± 3.9	47.7 ± 5.17	76.4 ± 3.9	47.5 ± 3.56	75.9 ± 4.2
WBLH FM	13.0 ± 3.6	20.5 ± 4.2	12.7 ± 3.4	20.3 ± 4.2	13.3 ± 4.0	20.8 ± 4.4
Kicking leg LSTM	8.9 ± 0.93	71.1 ± 4.5	9.0 ± 1.1	71.8 ± 3.6	8.9 ± 0.74	70.3 ± 5.5
Kicking leg FM	3.19 ± 0.89	25.1 ± 4.8	3.05 ± 0.67	24.3 ± 4.0	3.35 ± 1.1	26.0 ± 5.7
Kicking thigh LSTM	6.36 ± 0.70	71.5 ± 4.4	6.44 ± 0.80	72.1 ± 3.5	6.26 ± 0.60	70.7 ± 5.4
Kicking thigh FM	2.4 ± 0.65	26.0 ± 4.6	2.3 ± 0.58	25.3 ± 3.8	2.4 ± 0.76	26.8 ± 5.6
Kicking shank LSTM	2.12 ± 0.28	69.7 ± 6.3	2.13 ± 0.35	70.6 ± 6.2	2.11 ± 0.18	68.6 ± 6.6
Kicking shank FM	0.74 ± 0.27	23.8 ± 6.7	0.68 ± 0.20	22.6 ± 6.6	0.80 ± 0.34	25.1 ± 6.9
Calculated variables						
LSTM index (kg/m^2)	18.4 ± 1.0		18.2 ± 1.1		18.7 ± 0.9	
UB LSTM	30.2 ± 2.7	80.6 ± 4.1	30.1 ± 3.1	80.5 ± 4.6	30.3 ± 2.2	80.7 ± 3.7
UB FM	6.6 ± 2.1	17.5 ± 4.2	6.7 ± 2.2	17.6 ± 4.7	6.6 ± 2.0	17.4 ± 3.8
LB LSTM	17.8 ± 1.9	71.1 ± 4.3	17.9 ± 2.2	71.8 ± 3.6	17.6 ± 1.5	70.3 ± 5.1
LB FM	6.3 ± 1.7	25.0 ± 4.6	6.1 ± 1.3	24.3 ± 3.9	6.6 ± 2.1	25.9 ± 5.3
UB:LB LSTM	1.70 ± 0.08		1.69 ± 0.08		1.72 ± 0.07	
UB:LB FM	1.05 ± 0.16		1.08 ± 0.19		1.01 ± 0.10	
Total leg LSTM asymmetry %	2.61 ± 1.85		2.75 ± 2.35		2.43 ± 1.10	
Thigh LSTM asymmetry %	2.56 (1.83)		2.17 (2.29)		2.63 (1.50)	
Shank LSTM asymmetry %	2.67 (2.17)		2.61 (2.82)		2.72 (1.74)	

Data is presented as mean ± SD or Median (IQR) for non-normally distributed variables.
*Significantly ($p < 0.002$) different from 100% availability group; UB, Upper body; LB, Lower body; WBLH, whole body less head; LSTM, lean soft-tissue mass; FM, fat mass.

CDPR is weighted toward higher accumulated touches, effective use of the ball and gaining possession of the ball in a contested or disputed situation (20). CDPR are presented as an average of ranking points received per game played. CDPR was not used in games in which the player sustained an injury.

Average disposals, disposal efficiency, and kicking efficiency

Average disposals (AD), disposal efficiency (DE) and kicking efficiency (KE) data were retrieved from the official statistic supplier of the AFL (Champion Data ©, Melbourne, Australia). A disposal is an event whereby a player attempts to pass the ball to a teammate by kicking or handballing or is attempting a shot at goal *via* kicking (21). DE represents the proportion of disposals that each player had that were effective (the ball reached a desired teammate or went to a favorable/advantageous location). KE is a sub-group of DE and represents only kicking disposals (does not consider handballs) which also includes successful kicks at goal. Further definitions of AF statistics have been provided previously (22). Kicking and disposal accuracy/efficiency has been demonstrated to be important in the pathway to becoming an AFLW player (23). AD represents the average amount of disposals that each player had per game throughout the season. AFL coaches have been observed to perceive match performance more favorably for players with greater number of disposals and higher disposals and kicking efficiency (21). Kicking efficiency has also been previously linked with body composition characteristics in male AF players (24).

Statistical analysis

Descriptive statistics were acquired for the cohort of players using Python (v3.7.6) in source-code editor Visual Studio code (v1.61.0). Python packages used included Numpy, Pandas, Scipy, Seaborn and Matplotlib. All variables were assessed for normality using the Shapiro-Wilk test. Variables which were not normally distributed were log-transformed before conducting further analyses. LSTM index was calculated by dividing WBLH LSTM by player height. UB to LB LSTM and FM ratios were also calculated as well as LSTM asymmetry between limbs for each LB segment (total leg, thigh, shank). Pearson correlations (r) were calculated to quantify the correlation between all body composition variables with in-season match performance and availability. The correlation matrices were created using the Seaborn package in Python. Correlation coefficients were classified as 0–0.09 = trivial; 0.1–0.29 = small; 0.3–0.49 = moderate; 0.5–0.69 = large; 0.7–0.89 = very large and 0.9–0.99 = Near perfect (25). Players were then split into two sub-groups depending on their in-season match availability [<100% in-season match availability (n = 12), and 100% availability (n = 10)], representing a near 50/50 split within the cohort across the two groups. Two-sample independent t-tests were then conducted to examine the body composition differences that existed between the two groups. Due to the large number of analyses conducted on the same dependent variables, a Bonferroni correction was applied. Subsequently, an alpha level of $p < 0.002$ was considered statistically significant for two-sample independent t-tests. Finally, a median-split was implemented to separate players into a higher and lower performing group according to CDPR, CS, DE, KE and AD, which is an accepted technique (26). Two-sample independent t-tests were conducted to assess whether body composition differences existed between the groups.

Results

Descriptive player data for the entire group, and in-season match availability sub-groups are provided in Table 1. Significant differences between groups were observed for in-season match availability. No body composition variables significantly differentiated between in-season match availability according to sub-groups (100% season availability vs. <100% availability).

Further, no significant differences were observed for body composition characteristics between higher and lower performing groups for CDPR, CS, DE, KE or AD (Table 2). The only body composition variable significantly associated with match performance and availability was total leg LSTM asymmetry which shared a significant moderate negative association with CS ($\beta = -0.46$, 95% CI = -0.87 to-0.045) (Figure 1). In-season match performance and availability was not associated with any body composition characteristic expressed in absolute terms (Figure 2).

Discussion

This study investigated whether start of pre-season body composition characteristics were associated with in-season match performance, and match availability in elite female AF players. No body composition characteristics differentiated between the availability of athletes or between higher and lower performing players for CDPR, CS, DE, KE and AD. The AFLW season consisted of nine games across nine consecutive weeks from 29th January—28th March (not including finals). In comparison to the male league (AFL; 22 games), and other elite women's competitions, such as the Football Association women's Super League (Soccer; 22 games), the AFLW season is markedly shorter. Thus, a short season may reduce the relative influence of body composition as a notable contributing injury risk factor and match performance indicator in AFLW players. Further, due to the competition's recent establishment, the average playing experience across the cohort was only 3 years, which may highlight the limited capacity to detect a relationship here. Recent research discovered elite female senior AF players had superior intermittent running performance, sprint speed, vertical jump height and greater performance on technical kicking and handballing skill tests than their non-elite counterparts (14, 23). Thus, other factors such as muscular strength, aerobic fitness, technical skill, and pre-season training load exposure may be more important when examining in-season match performance and availability in AFLW players (14, 19, 27). While it has been suggested that FM has a negative effect on general body movement (28) and kicking accuracy in AF (24), the influence on match performance and availability across a nine-week season in women AF players (AFLW) appears minimal.

Greater body mass has previously been linked with lower injury risk in an elite male AF cohort, with every additional 1 kg of body mass decreasing injury risk by 11.3% (29). Whilst elite AF players cover ~13 kilometers (km) per game (3), players are also exposed to frequent heavy collisions which also places them at risk of contact injuries (10). It is likely that sufficient body mass (comprising muscle and fat) is required to absorb these forces and protect players from injury. Given the elite women's game is characterized by a greater proportion of contact injuries

TABLE 2 Differences between players according to a median split for match performance variables (Champion Data Player Rank, coaches score, disposal efficiency, kicking efficiency, and average disposals).

	<64 CDPR	>64 CDPR	<1.82 CS	>1.82 CS	<58.8% DE	>58.8% DE	<47.5% KE	>47.5% KE	<8.8 AD	>8.8 AD
Age (y)	26.4 ± 4.8	25.5 ± 4.3	26.1 ± 4.8	25.4 ± 4.1	26.1 ± 3.8	25.2 ± 5.0	25.9 ± 3.47	26.1 ± 5.6	26.7 ± 5.2	24.9 ± 3.4
Height (cm)	171 ± 7	168 ± 6	172 ± 7	168 ± 6	167 ± 6	171 ± 7	168 ± 6	170 ± 8	171 ± 7	168 ± 6
Body mass (kg)	68 ± 6	63 ± 7	66 ± 6	66 ± 8	64 ± 6	67 ± 8	64 ± 6	67 ± 8	67 ± 7	65 ± 6
LSTM Index (kg/m^2)	18.4 ± 1.1	18.4 ± 1.0	18.1 ± 0.89	18.7 ± 1.1	18.5 ± 1.1	18.3 ± 1.1	18.3 ± 0.9	18.5 ± 1.3	18.3 ± 1.1	18.5 ± 0.9
UB:LB LSTM	1.68 ± 0.06	1.73 ± 0.09	1.68 ± 0.05	1.72 ± 0.09	1.71 ± 0.09	1.70 ± 0.06	1.73 ± 0.08	1.69 ± 0.06	1.66 ± 0.04	1.74 ± 0.09
UB:LB FM	1.07 ± 0.20	1.01 ± 0.09	1.05 ± 0.18	1.05 ± 0.14	1.06 ± 0.14	1.05 ± 0.17	1.05 ± 0.16	1.03 ± 0.17	1.08 ± 0.20	1.02 ± 0.09
WBLH LSTM (kg)	48.4 ± 4.9	46.3 ± 3.7	48.0 ± 5.3	47.2 ± 3.6	46.5 ± 2.9	47.7 ± 5.4	46.6 ± 5.1	47.9 ± 3.9	48.2 ± 5.3	47.0 ± 3.5
WBLH FM (kg)	14.1 ± 2.9	11.7 ± 4.2	12.8 ± 1.7	13.1 ± 4.9	12.3 ± 4.4	13.7 ± 3.1	12.1 ± 2.6	13.5 ± 4.6	13.2 ± 3.3	12.8 ± 4.0
WBLH LSTM%	74.8 ± 3.7	77.6 ± 4.1	76.2 ± 2.6	76.1 ± 5.1	76.8 ± 4.9	75.3 ± 3.3	76.7 ± 3.8	75.8 ± 4.5	76.0 ± 3.9	76.4 ± 4.2
WBLH FM%	21.9 ± 4.0	19.1 ± 4.3	20.5 ± 2.8	20.5 ± 5.4	19.9 ± 5.2	21.5 ± 3.4	20.0 ± 4.1	20.8 ± 4.8	20.7 ± 4.2	20.3 ± 4.4
Kicking leg LSTM%	69.8 ± 3.8	72.3 ± 5.2	71.2 ± 3.0	71.0 ± 5.8	72.0 ± 5.1	70.0 ± 4.3	71.5 ± 4.3	70.7 ± 5.3	71.2 ± 3.6	71.0 ± 5.5
Kicking leg FM%	26.4 ± 4.0	23.8 ± 5.6	24.9 ± 3.2	25.2 ± 6.1	24.1 ± 5.4	26.3 ± 4.5	24.7 ± 4.6	25.4 ± 5.6	25.0 ± 3.9	25.1 ± 5.7
Support leg LSTM%	70.0 ± 3.3	72.1 ± 5.0	71.2 ± 3.0	71.0 ± 5.2	71.9 ± 4.6	70.1 ± 4.1	71.7 ± 3.9	70.6 ± 4.8	71.6 ± 3.8	70.6 ± 4.6
Support leg FM%	26.1 ± 3.5	23.9 ± 5.3	24.9 ± 3.2	25.2 ± 6.1	24.1 ± 4.9	26.2 ± 4.2	24.4 ± 4.1	25.4 ± 5.1	24.5 ± 4.1	25.4 ± 4.8
Kicking thigh LSTM%	70.0 ± 3.9	72.8 ± 4.9	71.6 ± 2.6	71.3 ± 5.9	72.2 ± 5.5	70.4 ± 3.6	72.1 ± 3.9	70.8 ± 5.4	71.5 ± 3.8	71.4 ± 5.2
Kicking thigh FM%	27.5 ± 4.0	24.6 ± 5.2	25.9 ± 2.7	26.1 ± 6.2	25.2 ± 5.7	27.2 ± 3.7	25.3 ± 4.0	26.7 ± 5.6	26.0 ± 4.0	26.0 ± 5.4
Support thigh LSTM%	70.2 ± 3.5	72.5 ± 4.8	71.4 ± 2.6	71.4 ± 5.4	72.2 ± 5.0	70.2 ± 3.5	72.0 ± 3.4	70.8 ± 5.2	71.8 ± 4.0	71.0 ± 4.5
Support thigh FM%	27.3 ± 3.6	24.7 ± 5.1	26.1 ± 2.7	25.9 ± 5.7	25.1 ± 5.3	27.3 ± 3.6	25.4 ± 3.5	26.6 ± 5.5	25.7 ± 4.2	26.3 ± 4.7
Kicking shank LSTM%	68.7 ± 6.2	70.8 ± 7.0	69.5 ± 5.9	69.9 ± 7.0	71.2 ± 5.8	68.4 ± 7.4	69.5 ± 7.3	70.2 ± 6.3	69.9 ± 5.7	69.5 ± 7.2
Kicking shank FM%	24.6 ± 6.5	22.9 ± 7.5	23.8 ± 6.1	23.7 ± 7.5	22.2 ± 6.1	25.3 ± 7.9	24.2 ± 7.6	23.1 ± 6.7	23.5 ± 5.9	24.1 ± 7.7
Support shank LSTM%	69.4 ± 5.0	71.1 ± 6.8	70.3 ± 5.3	70.5 ± 6.4	71.7 ± 5.4	69.2 ± 6.4	70.8 ± 6.5	70.1 ± 5.5	71.1 ± 5.2	69.6 ± 6.3
Support shank FM%	24.0 ± 5.1	22.5 ± 7.2	23.2 ± 5.2	23.1 ± 6.9	21.9 ± 5.7	24.5 ± 6.7	22.83 ± 6.7	23.24 ± 5.8	22.3 ± 5.22	24.0 ± 6.79
Total leg LSTM asymmetry %	2.43 ± 1.25	2.31 ± 1.86	2.99 ± 1.96	2.22 ± 1.74	2.13 ± 1.81	2.79 ± 1.15	1.91 ± 1.40	2.98 ± 1.54	3.40 ± 2.18	1.81 ± 1.03
Thigh LSTM asymmetry %	2.51 ± 1.18	2.82 ± 2.49	2.95 ± 2.58	3.00 ± 2.20	3.01 ± 2.32	2.57 ± 1.24	2.49 ± 1.10	3.00 ± 2.47	3.86 ± 2.92	2.08 ± 1.09
Shank LSTM asymmetry %	3.02 ± 2.25	2.92 ± 2.43	3.01 ± 2.09	2.90 ± 2.44	2.84 ± 2.57	3.27 ± 2.12	2.70 ± 1.25	3.43 ± 3.04	3.40 ± 2.90	2.51 ± 1.24

CDPR, Champion Data ® Player Rank; CS, Coaches Score; DE, Disposal efficiency; KE, Kicking efficiency; AD, Average disposals; UB, Upper body; LB, Lower body; WBLH, whole body less head; LSTM, lean soft-tissue mass; FM, fat mass.

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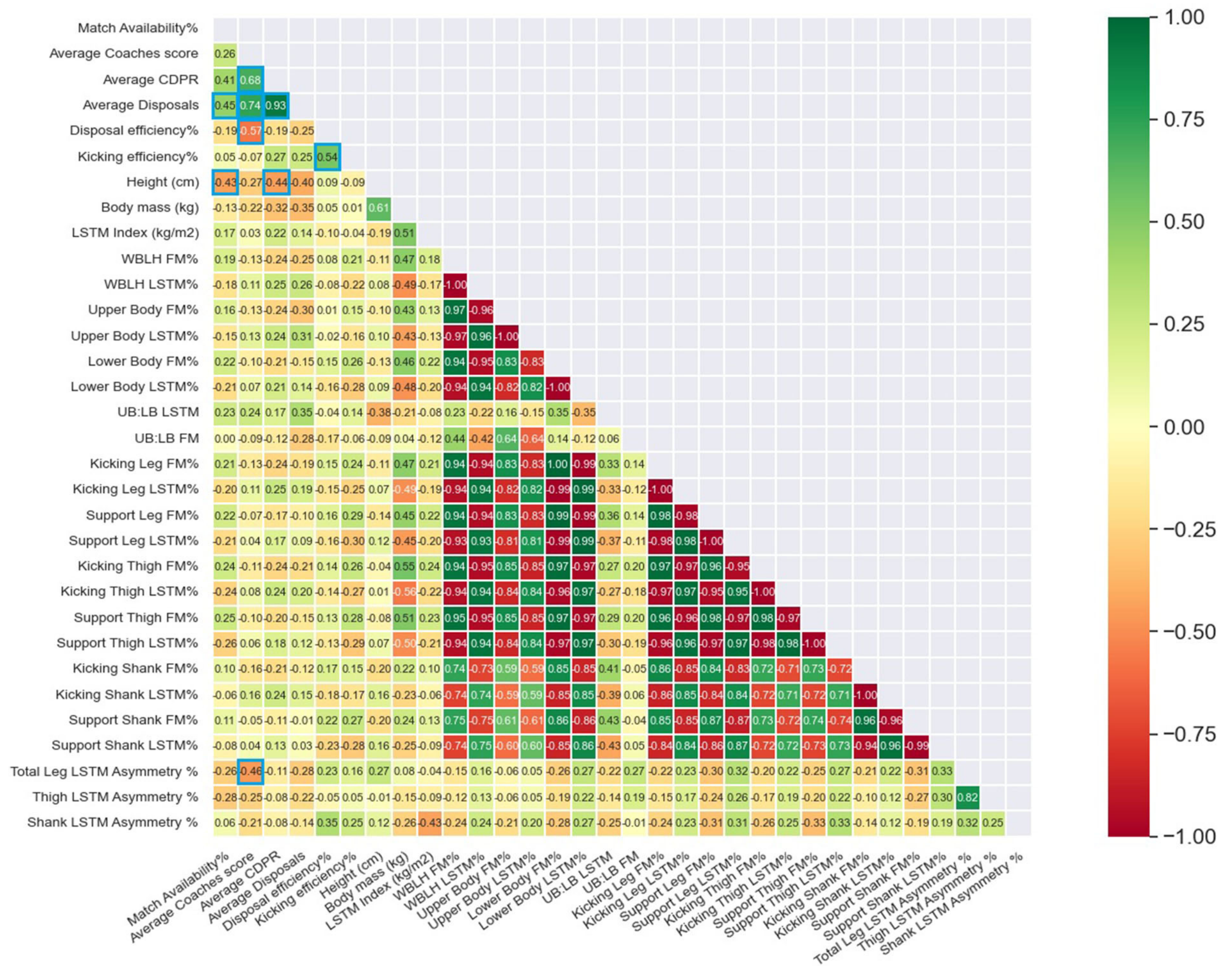

FIGURE 1
Pearson correlation matrix examining the association between pre-season body composition characteristics expressed as relative values, and in-season match availability and match performance. Significant ($p \leq 0.05$) relationships are represented by blue boxes. CDPR, Champion Data Player Rank; LSTM, Lean soft-tissue mass; UB, Upper body; LB, Lower body; FM, fat mass.

(9), and more contested possessions, tackles and stoppages per minute of play than the elite men's game (all of which increase the frequency of collisions) (5), it was hypothesized that greater muscle and body mass (as opposed to its composition) would be associated with higher match availability and performance (5, 30). However, in our study, no body composition characteristic, including total body mass, was associated with in-season match availability, suggesting other factors may be more influential in this relationship.

Similarly, no significant differences in body composition characteristics were observed between those players who were available for the entire season (100% availability) and those who missed at least one game due to injury throughout the season (<100% availability). This is in agreement with a study in elite professional rugby which found no relationship between body composition and injury (31). Conversely, whole body FM% has been positively associated with injury in male soccer players (32, 33). As the AFLW is a new and emerging competition with a current lack of developmental pathways, the league features many players who previously played other sports (including netball, basketball, and Gaelic Football). Thus, highlighting the fact that many players have not had the exposure to longitudinal AF specific loading and training history, which may place them at a greater risk of injury. Factoring this into the analysis may have provided more insight into this relationship. Further, females in the AFLW typically cover 50–70% less high-speed running distance per minute of match play than their elite male AFL counterparts (2, 3). As high-speed running induces neuromuscular fatigue and is considered a common mechanism for hamstring injury (34), AFLW players may not be at the same risk as elite male players comparatively. While body composition assessment has been banned from AFL and AFLW

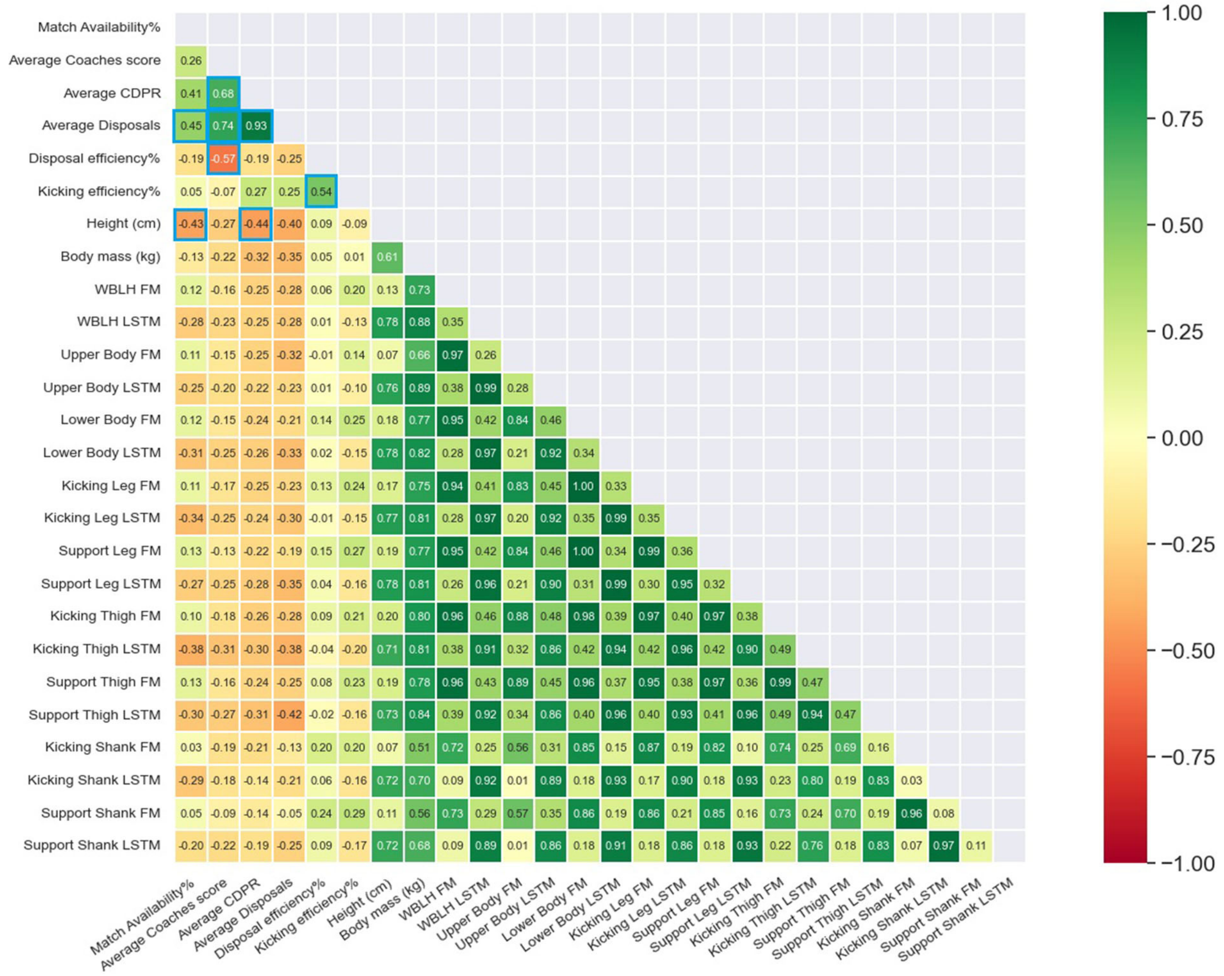

FIGURE 2
Pearson correlation matrix examining the association between pre-season body composition characteristics expressed as absolute values, and in-season match availability and match performance. Significant (p≤0.05) relationships are represented by blue boxes. CDPR, Champion Data Player Rank; LSTM, Lean soft-tissue mass; UB, Upper body; LB, Lower body; FM, fat mass.

pre-draft evaluations for other reasons, the results of this study indicate that body composition evaluated at the beginning of the pre-season for AFLW players may not be as important to match performance and in-season availability as may currently be perceived. This potentially highlights the greater importance of other attributes including aerobic fitness, and muscular power and strength with injury. Nonetheless, these findings present important insights for AFLW practitioners.

In the current study, match performance was determined both subjectively by the coaches and football department based on their perception of each player's impact on the game (CS) and objectively *via* CDPR, AD, DE and KE. However, no body composition characteristic could differentiate between higher and lower performing players for any match performance metric. As FM is known to impair cardiorespiratory performance by acting as "dead weight" and not contributing to force production and movement (28), it was hypothesized that lower levels of FM may allow players to cover more ground during a game, increasing their likelihood of having a greater impact on the game. By the same token, it was further conjectured that lower levels of FM may delay the onset of fatigue, lowering the risk of injury during a match. However, our data does not support such hypotheses. One explanation could be that the influence of FM in AFLW players is reduced due to the shorter match duration (~80 mins of match play vs. 120 mins in the AFL) and lower running volume [~6 vs. ~13 km (1, 3)] during competitive match play. Further, strength, power and technical skill are not as developed in the women's game and this is likely due to the disparities in training opportunities, development pathways, financial support and access to staff and facilities (35). Thus, it is likely that variations in these factors may overwhelm any minor influences that body composition has on in-season match performance and availability. This provides important insights for practitioners who should look to prioritize the development of other important attributes over specific body composition traits.

Interestingly, total leg LSTM asymmetry was the only body composition characteristic associated with any match performance metric (which shared a moderate negative relationship with Coaches Score). Research examining the relationship between LSTM asymmetry and sporting performance outcomes is scarce. Hart and colleagues (36) demonstrated that sub-elite AF players with greater kicking accuracy had significantly less leg LSTM asymmetry. However, LSTM asymmetry was not associated with kicking or disposal efficiency in the current study. LSTM asymmetries have been shown to influence jumping performance in collegiate athletes previously (37), but how this translates to match performance outcomes is unclear.

To our knowledge, this is the first study which has examined the relationship between pre-season body composition characteristics with in-season AFLW match performance and match availability. However, several limitations of this research are worth noting. First, body composition assessments were undertaken at the beginning of pre-season, roughly 3 months prior to the beginning of the competitive season. Thus, this may not be a true reflection of players' kinanthropometric profile throughout the competitive season as notable changes in body composition are likely to occur through targeted intervention across pre-season. Thus, start of pre-season body composition may be more a reflection of players' compliance to their off-season fitness program. Additionally, our results are delimited to 22 players at this one point in time, involving factors across one season. Thus, reducing the statistical power of the analyses. Smaller squad numbers (in comparison to elite male teams), contractual arrangements (which limits their time at the club), and the COVID-19 pandemic made data collection challenging. Future research should be directed to researching players over multiple teams and multiple seasons and multiple time points in the year while also considering the positional requirements and training history of each player. The results of this study also may not necessarily apply to other AFLW teams as all teams have varying levels of experience and an array of players who have crossed over from a variety of other sports.

Ultimately, no start of pre-season body composition characteristics were associated with in-season match availability, or most match performance metrics in female AF players playing in the AFLW. As the AFLW has only recently been established, other factors such as technical skill level, neuromuscular and cardiorespiratory capacities, and training history may share a greater association with in-season performance and availability. Body composition assessments have been banned as part of pre-draft evaluation of potential recruits and this study may provide justification that body composition is not as important as other physical and technical attributes in AFLW players. As the AFLW competition is still in its infancy, it's likely the physical and technical attributes are more variable between players and mask any influence that body composition has on in-season match availability and performance. As such, further research is needed to uncover the specific attributes linked with in-season match availability and performance in female AF players.

Data availability statement

The datasets presented in this article are not readily available because due to the agreement with the football club, no data outside of what has been illustrated in the manuscript can be made publicly available. Requests to access the datasets should be directed to c.mccaskie@ecu.edu.au.

Ethics statement

The studies involving human participants were reviewed and approved by Edith Cowan University Human Research Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

Author contributions

CM, NH, MS, RN, JH, and BR conceived and designed the research. CM, JH, and BR collected the data. CM analyzed the data with assistance from NH, MS, and RN. CM wrote the manuscript with assistance from all authors. All authors read and approved the manuscript.

Conflict of interest

Authors CM, JH, and BR were employed by West Coast Eagles Football Club.

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.

Publisher's note

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Cutting edge concepts: Does bilirubin enhance exercise performance?

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Exercise performance is dependent on many factors, such as muscular strength and endurance, cardiovascular capacity, liver health, and metabolic flexibility. Recent studies show that plasma levels of bilirubin, which has classically been viewed as a liver dysfunction biomarker, are elevated by exercise training and that elite athletes may have significantly higher levels. Other studies have shown higher plasma bilirubin levels in athletes and active individuals compared to general, sedentary populations. The reason for these adaptions is unclear, but it could be related to bilirubin's antioxidant properties in response to a large number of reactive oxygen species (ROS) that originates from mitochondria during exercise. However, the mechanisms of these are unknown. Current research has re-defined bilirubin as a metabolic hormone that interacts with nuclear receptors to drive gene transcription, which reduces body weight. Bilirubin has been shown to reduce adiposity and improve the cardiovascular system, which might be related to the adaption of bilirubin increasing during exercise. No studies have directly tested if elevating bilirubin levels can influence athletic performance. However, based on the mechanisms proposed in the present review, this seems plausible and an area to consider for future studies. Here, we discuss the importance of bilirubin and exercise and how the combination might improve metabolic health outcomes and possibly athletic performance.

KEYWORDS
exercise performance, heme oxygenase, biliverdin reductase, bilirubin, reactive oxygen species, oxidative stress, HO-1, BLVRA

Introduction

Exercise training can promote the physiological health of every organ system in the body, carrying a myriad of benefits, including improving blood glucose control, cardiovascular capacity, arterial compliance, skeletal muscle function, and energy metabolism (1–4). In fact, 35 chronic diseases or conditions have been independently linked to physical inactivity (5). Most health outcomes of regular exercise, such as improving aspects of the metabolic syndrome, depend on skeletal muscle adaptations (6). However, recent data has pointed to exercise-induced benefits in liver metabolism and function playing a vital role (7–9). Exercise increases hepatic glycogen mobilization when exercise bouts are sustained beyond short bursts of high-intensity activity that rely on intramuscular stores of glucose and fat (9, 10). As hepatic glycogen is reduced with extended exercise, the liver is also responsible for the uptake of gluconeogenic precursors such as lactate, pyruvate, ketones, and glycerol (10–13). This is accomplished, in part, by exercise-induced reductions in lipogenic processes and a simultaneous increase in the lipid oxidation (14, 15), a potential mechanism for how exercise can prevent liver diseases such as non-alcoholic fatty liver disease (NAFLD) (16, 17). Interestingly, a classical liver disease biomarker, bilirubin (11), has been shown to increase with exercise (18). Studies also show that increasing bilirubin levels decreases liver fat content and reduces oxidative stress in obese mice, improving adiposity and blood glucose (19–22). Other work has shown that aerobic exercise protects the liver and cardiometabolic health and adipose tissue remodeling under metabolic stress (23). These adaptations might be linked to glucose and fatty acid metabolism during exercise, which points to well-controlled crosstalk between the liver and skeletal muscle, exchanging substrates and maintaining metabolic homeostasis. Thus, exercise-induced adaptations centered on improving substrate utilization, also termed metabolic flexibility, are not solely dependent on the skeletal muscle metabolism (9, 10).

Exercise can also play an important role in weight control by aiding in attaining an energy deficit and the metabolic adaptations in the glucose and fatty-acid metabolism (24, 25). Although other aspects of metabolic syndrome can be improved with exercise alone (without weight loss), these benefits are substantially greater when significant weight loss occurs (26). While we later discuss that plasma bilirubin levels are elevated with exercise, another facet is that it also increases during weight loss (27). With the continually prevalent obesity epidemic, exercising for weight loss will continue to be a prevailing theme in research trials. It will be interesting to see whether bilirubin will be a measurable component of future works, especially since it has many protective properties that reduce oxidative stress.

An additional adaptation to exercise that may influence substrate utilization is the upregulation of antioxidant defense systems (18, 28, 29); this is partially due to increased ROS, and reactive nitrogen species (RNS) observed with exercise (30, 31). Such free radical production during exercise can have key regulatory roles in mediating various signaling processes. However, when increases in free radicals are not met with increases in antioxidant defense, pathophysiological states such as inflammatory, cardiovascular, and neurodegenerative diseases may manifest (32). Recent research has focused on oxidative stress and exercise mechanisms, with many exploring the utility of additional antioxidant supplementation when engaging in consistent exercise (18, 33, 34). New findings have revealed that the antioxidant bilirubin may be significantly elevated in athletes (18, 35). Other recent works have shown that bilirubin has a hormonal function that reduces body weight and may be related to exercise capacity (19, 36–44). These findings point to bilirubin as an underlying mediator of exercise-induced alterations in substrate oxidation, weight loss, antioxidant status, and a surrogate to the aforementioned health outcomes (37, 38, 42, 44). Herein, we will delve into the recent literature investigating the link between bilirubin, exercise, and physiological health.

Bilirubin and exercise

Traditionally viewed as a marker for liver damage, bilirubin is becoming recognized as an important endocrine hormone and a potent antioxidant that activates nuclear receptors to control gene transcription that promotes many aspects of physiological health (cardiovascular health, blood glucose control, oxidative stress, and improves liver function) (37, 39, 43, 45). The medical community has defined “normal” total plasma bilirubin levels as 1.7–20 µmol/L, while the Child-Pugh index indicates a value of >51 µmol/L is indicative of decompensated liver cirrhosis. Large variations in plasma bilirubin are exhibited among the general population due to age, sex, ethnicity, and other biological factors. Thus, it is difficult to define a particular range for other non-clinical conditions such as long-term exercise, acute exercise, obesity, and lean individuals (46). The concept of hypobilirubinemia has been recently proposed at levels of plasma/serum bilirubin <10 µmol/L [discussed further in (37)].

Bilirubin originates from hemoglobin released from myoglobin and other hemoproteins during the destruction of senescent red blood cells. When a blood cell dies and is lysed, which occurs mostly in the spleen, heme is released and converted to biliverdin by heme oxygenase (HO), which is further metabolized to bilirubin by biliverdin reductase A (BVRA) (**Figure 1**) (47). Blood bilirubin levels have previously been thought only to be derived from reticuloendothelial cells in the spleen (37). However, studies in mice lacking BVRA (21, 48–50) have shown that bilirubin generation also occurs in many other tissues. Lastly, bilirubin is conjugated by the UDP-glucuronosyltransferase enzyme, UGT1A1 (51), which then deposits the conjugated bilirubin in the bile (43). Thus, it is possible to regulate plasma bilirubin levels by regulating HO, BVRA, or UGT1A1. Recently published work showed that high-capacity running rats (HCR), compared to low-capacity running rats (LCR), had significantly higher plasma bilirubin, which was likely due

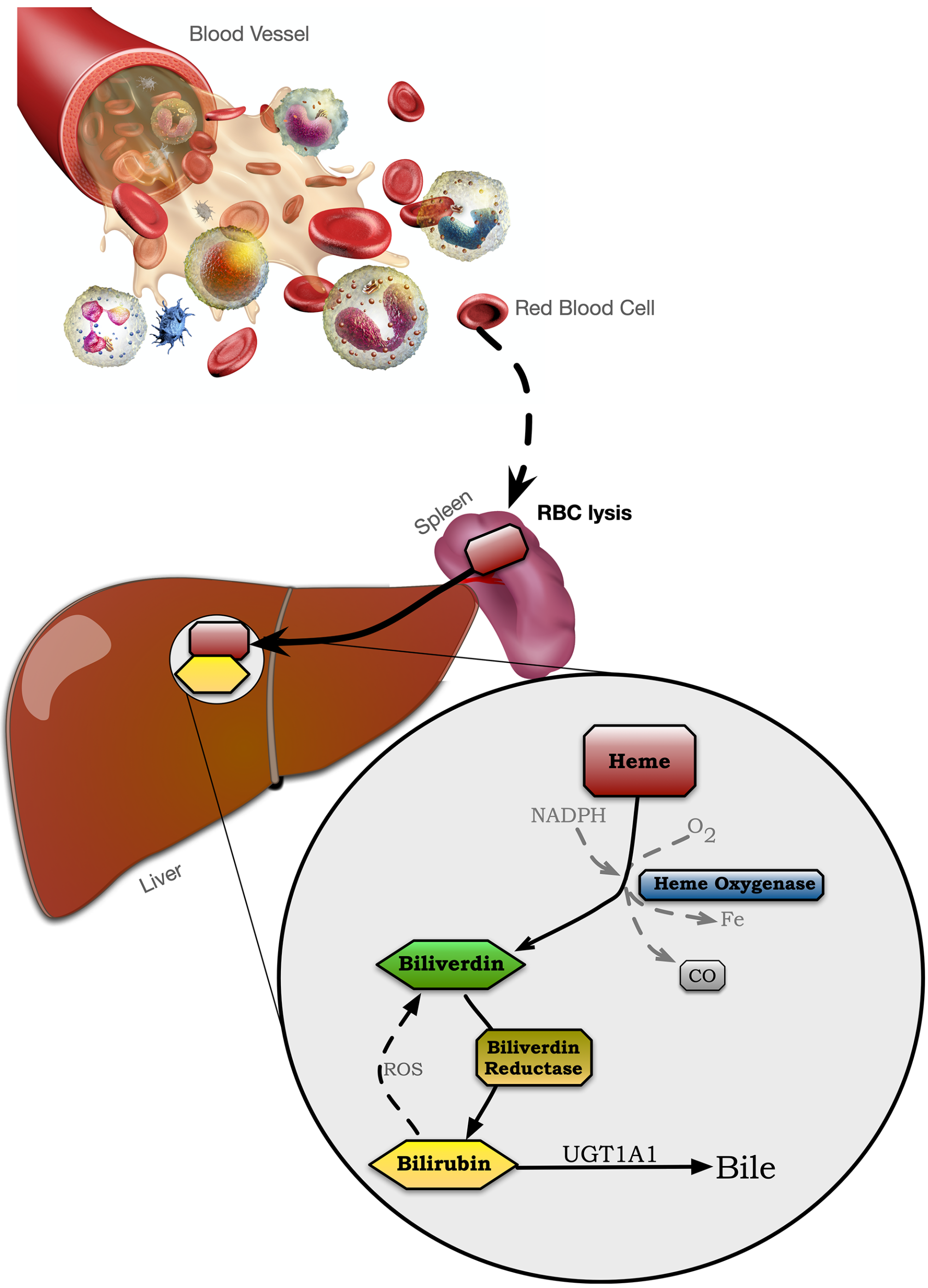

FIGURE 1
The heme oxygenase-bilirubin pathway.

to hepatic BVRA being raised and UGT1A1 lowered (52). These ultimately cause higher bilirubin production by BVRA and less bilirubin clearance *via* UGT1A1 conjugation.

Although research connecting bilirubin and exercise is in its infancy, a limited number of studies have demonstrated that bilirubin may be increased with both acute and regular (long-term) endurance exercise in animal models and humans (52–55). This was observed in the Dose-Response to Exercise in Women Trial (DREW Trial), where participants were placed in three groups of varying exercise volumes (4, 8, or 12 kcal.kg.week) for 12 weeks, demonstrating bilirubin only increased in the 12 kcal.kg.week group, equivalent to an average of 169 min per week (54). This dose-response relationship is supported by a separate trial where 12 weeks of exercise training that progressed to 120 min per week did not influence bilirubin levels (56). Thus, exercise meeting or slightly exceeding the recommended 150 min of moderate to vigorous physical activity per week appears necessary to observe physiological (beneficial) increases in the plasma bilirubin (57). This is also supported in less controlled trials, where bilirubin increases after 3 months of soccer or rugby training in competitive athletes (58, 59) and is elevated in competitive athletes compared to the general population (35, 60). Associations have also been drawn between usual exercise behavior, where aerobic and strength training participation was positively related to plasma bilirubin levels among women. In contrast, only aerobic training participation was positively correlated in the men (61). There is also evidence that an acute bout of exercise (often exhaustive) can upregulate plasma bilirubin. This was demonstrated in trained and untrained adults and adolescents after a running time trial test to exhaustion (62). A maximal exercise test also increased plasma bilirubin among football players (63) and was increased 4 days after an ultra-marathon among trained runners (64).

An important question yet to be fully elucidated is the mechanisms induced by exercise that cause the reciprocal increase in plasma bilirubin (**Figure 2**). One theory is that heme catabolism could result from exercise (especially aerobic exercise) induced damage such as repeated foot strikes, elevated core temps, and skeletal muscle breakdown (myoglobin release) (65, 66). In this scenario, red blood cells may become lysed and release heme (hemolysis). This released heme can be broken down to biliverdin by heme oxygenase-1 (HO-1) and further catabolized by BVRA to eventually form a stable, unconjugated bilirubin (43). This view is supported by several of the findings above, where only the highest dose of exercise, which had the greatest exposure to factors associated with exercise-induced hemolysis, observed increases in the plasma bilirubin (54). This logic could also be applied to trained athletes exposed to very high levels of factors that may induce hemolysis to promote the observed elevations in bilirubin levels (35, 58–60). However, Swift et al. did not detect changes in hemoglobin or hematocrit following exercise training (54). This has been supported by Witek et al.'s work on athletes, who concluded that the hematological parameters did not indicate the occurrence of increased hemolysis, with no significant relationship between the total bilirubin concentration and the number of red blood cells, hemoglobin, or iron levels in the blood of trained athletes (60). These results are similar to those of Andelkovic et al., where 3 months of soccer training did not increase serum iron (likely to reflect hemolysis) nor transferrin (likely to reflect erythropoiesis due to increased hemolysis) (58). Although this study also demonstrated increased serum ferritin after training and positive correlations between bilirubin and ferritin post-training (58). Since ferritin is known to sequester iron in the blood, increased ferritin levels may mask the elevations in iron resulting from exercise-induced hemolysis; an antioxidant adaptation of ferritin has been previously demonstrated (67, 68). However, this has not been consistent across studies, with many showing no changes or decreases in ferritin after long-term exercise training in athletes' (69–71). Other arguments against exercise-induced hemolysis driving greater bilirubin levels seen in athletes or after a long-term intervention are the notion that markers of hemolysis are typically present only immediately after intense exercise (63, 66), which would support why plasma bilirubin can increase after a bout of acute exercise (62–64).

Another hypothesis is that exercise-induced increases in bilirubin are the result of a feedback mechanism to regulate the increased oxidative stress that accompanies physical training (35). As noted, bilirubin is a powerful antioxidant, and if following other antioxidant defense systems, it should increase with long-term exercise training to better control exercise-induced free radical damage (18, 28, 29). Indeed, the long-term exercise effect on bilirubin is associated with an increase in other antioxidant reserves as well, including total antioxidant status (35). Such increases in bilirubin would likely result from greater HO activity, which is increased with exercise training (72). Since HO is the rate-limiting enzyme necessary for converting heme to biliverdin (73), greater HO levels could force the observed increase in plasma bilirubin after long-term exercise or in physical activity individuals/athletes. Other mechanisms promoting an exercise-induced increase in plasma bilirubin could involve the enzyme that converts biliverdin to bilirubin (BVRA) (74) or the enzyme that is responsible for the removal of bilirubin from the blood into bile (UGT1A1). As noted, HCR mice demonstrated higher plasma bilirubin and increased BVRA expression while UGT1A1 was decreased compared to control animals (52). Interestingly, hepatic HO-1 was not different between the HCR mice and control, despite large differences in distance and time run to exhaustion. This indicates that exercise-induced increases in bilirubin can stem from changes in several different enzymes, including HO-1, BVRA, and UGT1A1 (**Figure 1**). It seems likely that long-term adaptations to exercise training promote antioxidant defenses, including bilirubin, while short-term adaptations include those related to exercise-induced damage and increased heme availability.

Gilbert's syndrome and exercise

Although it seems that regular physical training leads to an elevation in serum bilirubin concentrations, additional considerations need to be given to Gilbert's Syndrome (GS), a genetic polymorphism that reduces UGT1A1 expression,

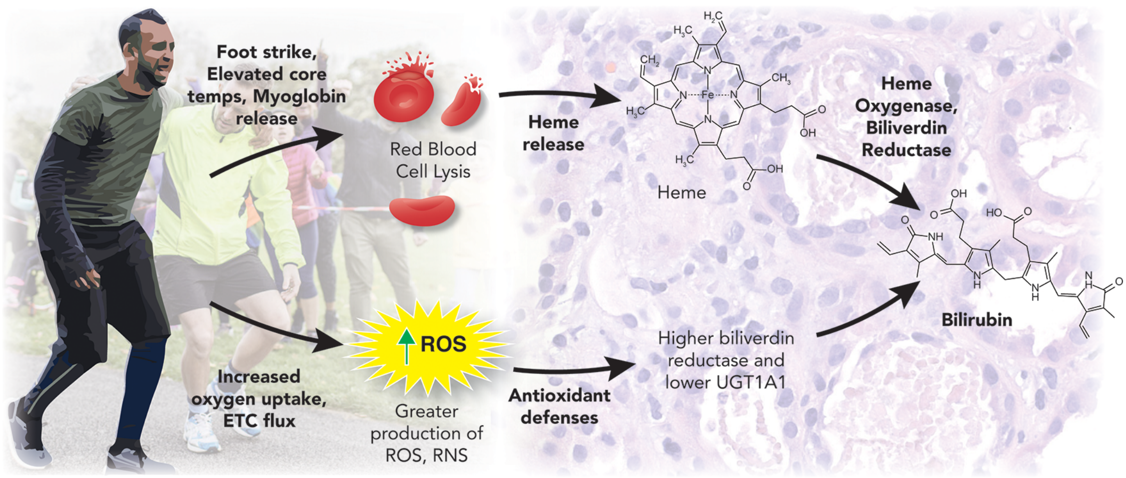

FIGURE 2
Exercise and bilirubin production. This figure was created by Matthew Hazzard at the University of Kentucky College of Medicine.

increasing plasma bilirubin levels to potentially influence athletic performance (53). This has been demonstrated in elite Czech athletes, where elite sportsmen and sportswomen had significantly greater serum bilirubin concentrations (8.5–16 µmol/L) compared to the general population (53). At the same time, the prevalence rate of phenotypic GS syndrome was also much higher in elite athletes, suggesting that a mild elevation of serum bilirubin might predispose to better sports performance. In other words, mildly hyperbilirubinemic elite athletes could have been selected based on this biochemical trait to reach the sport's elite. This provides further evidence that bilirubin may promote athletic performance, likely related to bilirubin's role as an endocrine hormone, inducing gene transcription that modulates metabolic functions. Increased systemic concentrations of bilirubin may represent a feedback mechanism to:

a) cope with the increased oxidative stress that accompanies the training process (30),
b) provide signaling stimuli to the muscle (75) and cardiovascular system (76), improve adaptation to physical training stress, and simultaneously,
c) provide substantial metabolic advantages regarding fatty acid oxidation associated with regular exercise (77).

These conclusions are based on recent observations. Regular exercise has been associated with increased antioxidant capacity, similar to a previous report documenting an exercise-induced increase in other body antioxidant reserves (62). In addition, bilirubin is an important signaling molecule (78, 79), fulfilling parameters of the endocrine substance (45). Therefore, these activities are highly likely to contribute to the beneficiary metabolic adaptations associated with regular training.

Bilirubin and cardiovascular system as a benefit for exercise

Increased plasma bilirubin levels can have several beneficial effects on the cardiovascular system in the context of exercise (**Figure 3**). First, bilirubin is a potent antioxidant compound that can scavenge ROS both directly and through the inhibition of the NAD(P)H oxidase (80, 81). One of the main targets of the ROS product superoxide anion ($O_2^{\bullet}$) is nitric oxide (NO). Superoxide interacts with NO to form peroxynitrite radical, damaging DNA and nitrosylate tyrosine residues, which disrupts protein function. By limiting the production and actions of superoxide, bilirubin can increase the bioavailability of NO to preserve the blood flow (82–84). The preservation of blood flow through enhanced NO bioavailability may mediate the improvement in athletic performance observed with increased levels of plasma bilirubin (35). Bilirubin mimics the protective actions of HO-1 induction and restores attenuated eNOS expression after exposure to oxLDL and TNF-α (85). The hyperbilirubinemic Gunn rat is resistant to the pressor actions of angiotensin II, and bilirubin can attenuate the release of endothelin-1 (86, 87). These findings demonstrate that bilirubin has vasoprotective actions, which could be beneficial to maintaining blood flow during exercise.

Recent studies have indicated that bilirubin functions as a hormone to activate the nuclear receptor peroxisome proliferator-activated receptor alpha (PPARα). It has been proposed that low plasma bilirubin levels should be considered a pathological state (37, 44). PPARα activation in the liver is a contributory factor to the exercise-related improvements in the whole-body metabolism (88). In fact,

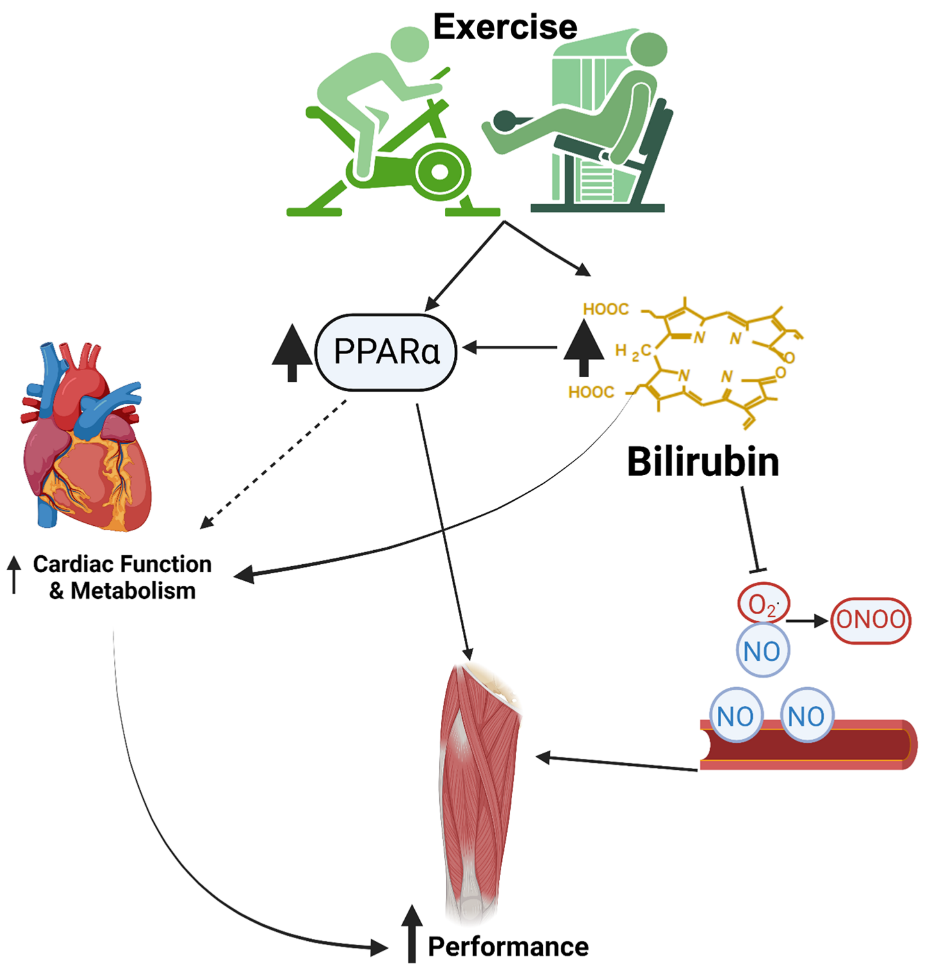

FIGURE 3
Cardiovascular benefits of exercise and bilirubin. This image was made using Biorender.com.

induction of PPARα in the vasculature by exercise has recently been proposed as a therapy to fight COVID-19 infection (89). Gene polymorphisms in PPARα increase physical and aerobic performance and are associated with muscle fiber type composition in athletes' (90, 91). Twice a day, close proximity exercise is associated with enhanced mitochondrial biogenesis, fat oxidation, and upregulation of skeletal muscle PPARα (92). Likewise, treatment with the PPARα agonist, fenofibrate, increases soleus muscle weight and enhances musculoskeletal training response during estrogen deficiency in ovariectomized (OVX) Sprague Dawley rats (93). Exercise training also decreases the age-related decline in cardiac PPARα levels in rats (94). PPARα knockout mice exhibited reduced lipolysis and anti-inflammatory responses in adipose tissue following exercise (95). The adipose-specific PPARα KO (96) and liver-specific PPARα KO (97) animals exhibited adiposity in the null tissues, which further indicates the importance of the bilirubin-PPARα circuit.

PPARα affects changes in metabolism central to exercise adaptation and muscle stem cell dynamics. Satellite cells, the *bonafide* muscle stem cell, support skeletal muscle exercise adaptation through activation and fusion into muscle fibers (98–100). Exercise-induced satellite cell activation is reliant on dynamic metabolic reprogramming culminating in robust activation of oxidative metabolism during the terminal differentiation (101). PPARα is a critical regulator of muscle lipid homeostasis to facilitate differentiation of human satellite cells *in vitro* to support subsequent fusion into muscle fibers to facilitate exercise-induced adaptation (102, 103). Furthermore, skeletal muscle is a mosaic of different fiber "types" uniquely defined by their metabolic requirement. The targeting by PPARα of genes involved in cellular fatty acid import and binding help define a unique cellular identity for PPARα in oxidative type I fibers versus the predominantly glycolytic type II muscle fibers (104). Greater demand for mitochondrial biogenesis and oxidative metabolism that occur in response to chronic exercise supports a fiber type-specific role for PPARα-mediated transcription. Variance in human type I fiber distribution is closely associated with PPARα expression, offering further support for PPARα in the distinct metabolic requirements of oxidative, slow twitch type I fibers (105). Further studies in PPARα deficient animals are needed in order to fully elucidate the role of PPARα activation in response to increases in bilirubin production in exercise.

Bilirubin is also cardio-protective, and increased bilirubin levels during exercise may benefit the heart. For example, studies in hyperbilirubinemic Gunn rats demonstrate that bilirubin protects the heart from reperfusion injury and beneficially influences aortic ejection velocities and pressures, improving cardiac performance during exercise (106, 107). Recent studies have demonstrated that bilirubin can increase the production of hepatic ketone beta-hydroxybutyrate (BOHB) (19), which likely occurred *via* PPARα mechanisms. A diet supplemented with BOHB precursors improved exercise performance in rats (108). Ketones may play an important role in the metabolic adaptation of the heart to exercise, especially in type II diabetic patients who are unable to effectively utilize glucose as a cardiac energy source. While the protective actions of bilirubin on the heart have largely been explained through its potent antioxidant activity, the effects of bilirubin on cardiac metabolism remain to be thoroughly studied. It is possible that bilirubin plays an important role in the metabolic adaptation of the heart to exercise both directly and indirectly through its action on PPARα and hepatic production of BOHB.

There is mounting evidence pointing to bilirubin as an important hormonal molecule and antioxidant, a departure from the traditional view that the role of bilirubin was limited to a marker for liver dysfunction. Bilirubin's role in mediating metabolic adaptations and protecting from oxidative stress is now evident, most notably in the context of cardiovascular disease and obesity. The present review has further explored the role exercise training appears to have on bilirubin levels, outlining two primary metabolic pathways activated by exercise that promote slight elevations in plasma bilirubin. The first of these pathways are related to heme catabolism, where exercise-induced damage such as muscle strain causing myoglobin release, elevated core temperature, and repetitive foot strike causes red blood cell lysis and heme release. Using heme as a precursor, through actions of the HO and BVRA enzymes, bilirubin synthesis is increased. This pathway seems to be impacted primarily by acute exercise, as reductions in hemolysis can be a long-term training adaptation observed among athletes (69–71). An additional pathway that can increase exercise-induced elevations in plasma bilirubin is related to an upregulation of antioxidant defense mechanisms. Just as other antioxidant enzymes are increased in response to elevations in ROS and RNS that accompany exercise (62), including total antioxidant status (35), BVRA can be increased while the enzyme UGT1A1 is decreased, thus promoting the synthesis and increased plasma levels of bilirubin (52). The combination of both pathways explains how both long-term and acute exercise can promote bilirubin levels and why athletes have consistently demonstrated greater plasma bilirubin levels compared to the general population.

Conclusion

Although no studies have directly tested if increasing plasma bilirubin levels promote improved exercise performance, this hypothesis seems probable with the evidence presented and an area for future research exploration. Preliminary evidence that supports this hypothesis is related to studies on GS and elite athlete performance. These individuals have a specific genetic polymorphism that causes elevated plasma bilirubin, where a far greater prevalence of GS is observed in elite athletes. This suggests that individuals with greater bilirubin levels might be predisposed to greater athletic performance. This could be related to bilirubin's role as a hormonal signaling molecule, where bilirubin interacts with PPARα to stimulate gene transcription related to fatty acid oxidative and mitochondrial capacities, important mediators in muscle function and exercise performance (102, 103). Improving antioxidant defenses through elevations in bilirubin is also desirable for athletic performance, likely related to enhanced bioavailability of NO and increased blood flow (35, 82–84). Controlled trials in humans testing the potential utility of bilirubin playing an ergogenic role in exercise performance are lacking and, thus, an additional avenue for future investigation. The optimal level of plasma bilirubin has also not been defined for health or athletic performance, another important question that research may address. Altogether, future work to determine whether increasing plasma bilirubin levels are useful for enhancing athletic performance is needed before research can focus on ergogenic aids to increase plasma bilirubin. In the least, bilirubin is an important molecule and new hormone that improves metabolic function and could be an essential metabolite of exercise performance and weight loss.

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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Conflict of interest

TH and DS have submitted patents on bilirubin and obesity-related disorders. 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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Connected model to optimize performance

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Introduction

The analysis and prediction of running performance have been the subject of much research. Several tools using the relationship between distance (or speed) and its time limit, as well as physiological models were developed to understand human endurance and to explain performance based on physiological parameters (1–3). Tables (4), mathematical equations (e.g., logarithmic, hyperbolic, exponential, linear…) (5–7) including the concepts of critical speed (8, 9) or power law (3, 10), nomograms (11, 12), and Artificial Intelligence (AI) algorithms (13, 14) are notable examples. Although many approaches are valid and accurate to predict performance over a given distance (e.g., nomograms, concept of critical velocity or power law…) (15), these approaches notably allow the prediction of a "final time", which could be commonly referred to as performance. It is not uncommon for the running performance predictions are based on the theoretical calculation of running time using the best performance(s) achieved over other distances, and on some equivalence between the time references of the different distances covered (12, 15–17). However, prediction approaches, more and more elaborate considering empirical, biomechanical or physiological data, have been developed over the years (18, 19), notably through the evolution of technologies such as AI (14, 19, 20). These prediction approaches can be useful for calibrating, quantifying sessions, but also detecting, for example, future athletes with high potential (16, 17, 19, 21). They can also provide additional information (e.g., identify specific training intensities…) (16, 17, 21) to traditional laboratory methods measuring the main physiological parameters of running performance (e.g., maximal oxygen uptake: $\dot{V}O_{2max}$, maximum aerobic speed, aerobic endurance capacity, etc.) (8, 22). However, beyond the predicted time, it could be interesting to question the conditions for achieving this final time, in other words, to question the "path" that the athlete should take to reach it. Indeed, if performance prediction can be useful to optimize performance, to define specific training intensities, to plan split times during competitions (16, 17, 21), this does not necessarily mean that the average speed obtained through the predicted final time, to achieve performance, must be constant throughout the distance covered. The approaching condition of running could then be rethought other than by the fact that a constant or regular speed is ideal by focusing in particular on other physiological parameters than $\dot{V}O_{2max}$, the energy cost and the endurance capacity commonly used in performance modeling [i.e., paradigm of constant speed from the Di Prampero equation (23)]. To achieve a performance, we could for example ask ourselves about the optimal speed (e.g., target speed) and the strategy for managing it (e.g., constant speed, pace variation…) but also the conditions for achieving it (e.g., weather conditions, race profile, diet, sleep, sports equipment, technologies…), which can delay voluntary exhaustion, but also allow running the given distance as quickly as possible (24–31). To contextualise this, we can take the example of the "Ineos 1:59 Challenge" project, where Kenyan Eliud Kipchoge aimed to break the iconic 2-h barrier in the marathon. The result is that strategies such as a relatively "regular" running pace (i.e., 2 min 49 s per km) as well as the use of "new generation" running shoes (e.g., shoes with carbon plates and rubber) have proven to be effective, It should be noted that a similar event took place in the United States in the early 1990s, where the runners' performance was not homologated by World Athletics for various reasons (e.g., intermittent pacers, car emitting a laser beam…). From these observations, we can then be led to wonder beyond the final time that could be predicted, about the "ideal" running pattern that could optimise running performance while taking into consideration (e.g., in real time from connected objects…) the multifactorial aspect of the latter (i.e., physiological, biomechanical, psychological, environmental and technological factors) (cf. **Figure 1**) (24–31). Therefore, the aim of this opinion is to try to answer these questions. For this, we consider turning to Big Data (i.e., megadata collected to designate a set of digital data produced by the use of new technologies) and AI, which seem to offer new work perspectives for the prediction of sports performance (13, 20, 32–36).

The current landscape

Big data and connected technologies

At present, increasing amounts of data are collected in many disciplines including running, in particular through sensors (e.g., Global Positioning Sensor: GPS, accelerometer, heart rate monitor…), connected objects (e.g., smart meters such as watches, glasses, textiles, insoles…) (37–39) content published on databases (e.g., performance, split times during competitions, results…). If we are interested, for example, at these data commonly collected in running *via* connected devices and/or smartphone applications (e.g., Strava®, Garmin®, Runtastic®…) (40), the latter can make it possible to analyze, or even predict, performance by monitoring several variables (e.g., pace or speed of movement, variation in the altitude difference of the course, amplitude and frequency of strides…) in a non-invasive way in real conditions (i.e., with possible real-time feedback) and especially outside a laboratory (14, 34, 37, 41–43). The research of Emig and Peltonen (34), Smyth and Muniz-Pumares (30) has notably highlighted mathematical modelling based on the use of connected wearable technologies such as wrist devices (e.g., connected watches) or smartphones to correlate performance indices with the volume and intensity of training in order to quantify, for example, the optimal training load. These studies (30, 34) have chosen to integrate in their algorithms (already taking into consideration past references on the target distance), the runners' training regime (e.g., distance, time, running pace and elevation gain) 6 weeks before the prepared competition. The use of these connected technologies and Big Data, suggests new ways of quantifying and predicting athletic performance in real conditions. Other technologies, still not widely used in the running world, such as connected insoles could also allow the collection and exploitation of new data in order to understand and optimize sports performance (e.g., integration of these data in prediction algorithms) (44, 45). However, beyond the quality of the recovered data (i.e., precision, accuracy with over or underestimation of raw values, like recorded energy expenditure depending running intensities, but also distances significantly underestimated and less accurate in the forest areas to the road area, that can highlight the limitations of connected objects) (46–48), the exploitation of these data could be complex in view of the quantity of available data (Big Data) obtained through connected technologies. What methodology/approach could then respond to this Big Data problem?

Artificial intelligence

AI used in many fields of science (e.g., meteorology, medicine, sport sciences…) (32, 49, 50) suggests new ways of quantifying and predicting sports performance in real-life conditions, given the scientific publications obtained in recent years. Indeed, Hammerling et al. (20) performed predictions of race times in the 2013 Boston Marathon for all runners who reached the halfway point of the race but did not have the opportunity to cross the line due to an attack (i.e., interruption of the race following the explosion of two bombs placed near the finish line) and thus to recognize the achievements of these runners. To make these predictions, Hammerling et al. (20) used a database of all previous years' performances at the same event (i.e., Boston Marathon of 2010 and 2011) and took into account the "real" times (i.e., time intervals of 5 km as well as the final 2,195 km) of the runners engaged in this event before they were interrupted by the organization. The use of different AI algorithms including K-Nearest Neighbors (KNN), made it possible to predict the performance of all the runners (i.e., a final time based on the prediction of intermediate times), i.e., the time they could have achieved over the distance, to establish a ranking of the

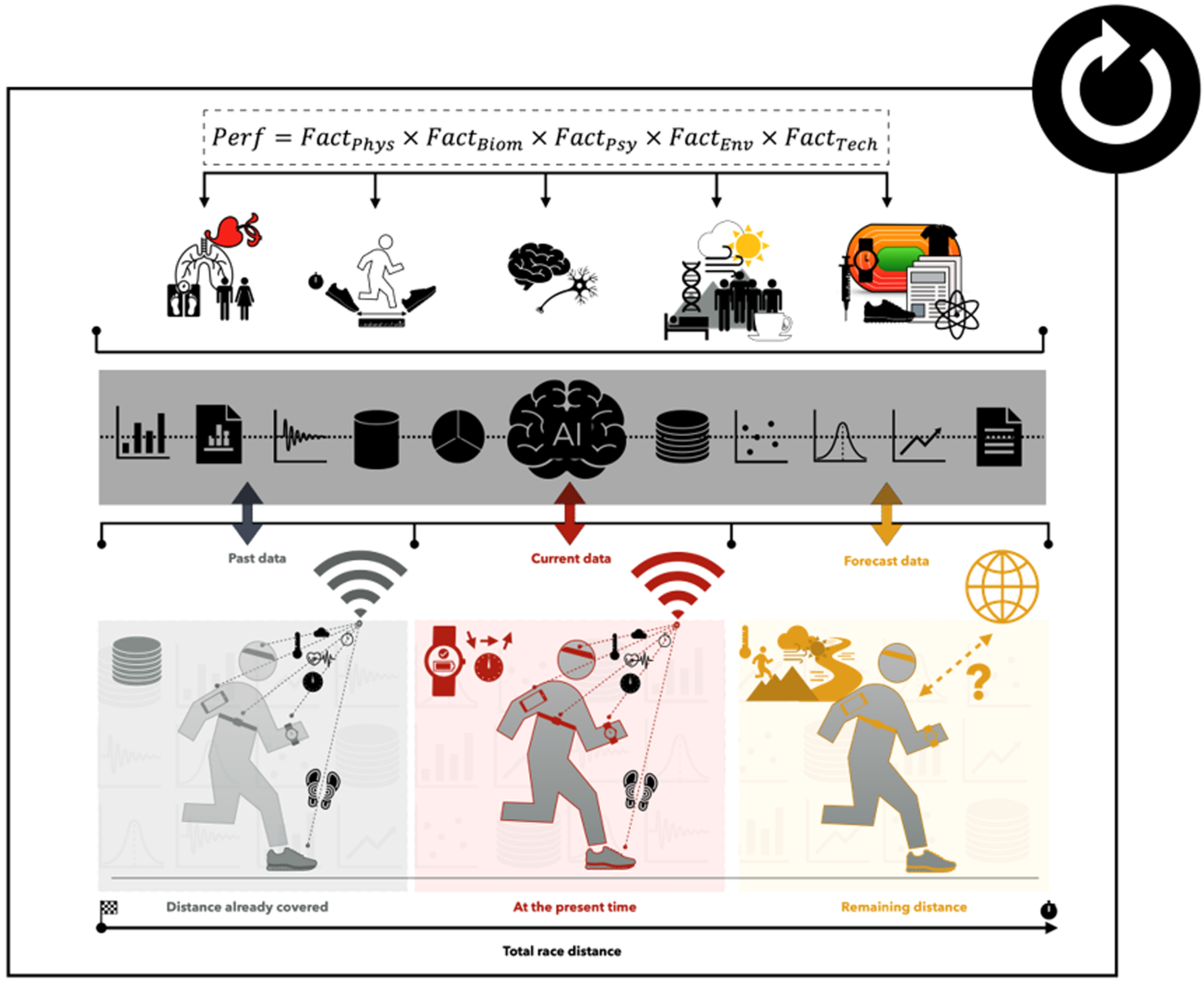

FIGURE 1
Illustration of a "connected multifactorial" intelligent model capable of adapting in "real" time during the effort to optimize running performance. $Fact_{Phys}$ (physiological factor), $Fact_{Biom}$ (biomechanical factor), $Fact_{Psy}$ (psychological factor), $Fact_{Env}$ (environmental factor), $Fact_{Tech}$ (technological factor), AI (artificial intelligence).

runners involved in this event. To do this, authors created an independent validation dataset from a fraction of the runners (25.7%) who finished the race and then ran dropout simulations at various points of the race on these runners in the same proportion as the true runners who unfortunately did not finish. The predicted finish times of this sample of fake runners who drop out were then compared with the actual finish times of these runners to assess the effectiveness of the statistical approaches. These predictions shown to be relatively accurate (i.e., Mean Absolute Error of 1 min 30 s on average) with an increased accuracy for runners who had to abandon later. In addition, beyond the prediction of performance, *via* AI, based on real data recovered during competitions, other work (14) has highlighted the use of supervised learning algorithms based on real training conditions in amateur runners to predict marathon performance, for example.

Modelling project

Given the multifactorial aspect of performance (25–31, 51) and the fact that performance prediction is a subject of great interest to athletes and coaches, we could "legitimately" ask ourselves what future prediction models might look like? Taking into account previous work in this field of AI and the current evolution of connected technologies such as textiles or insoles, would the challenge then be to think of an approach, an equation that is able to "simply" optimize a large number of factors correlated with past data (e.g., data based on training program or even the start of a race), "actual" (i.e., data obtained in real time, such as heart rate) and/or future (e.g., estimates based on future conditions and forecasts during a race, such as changes in weather conditions) of running performance by connected objects? Could we not try to propose a multifactor equation:

$$Perf = Fact_{Phys} \times Fact_{Biom} \times Fact_{Psy} \times Fact_{Env} \times Fact_{Tech}$$

where each physiological ($Fact_{Phys}$), biomechanical ($Fact_{Biom}$), psychological ($Fact_{Psy}$), environmental ($Fact_{Env}$) and/or technological ($Fact_{Tech}$) factor would be expressed through the intermediary and preponderance of indices conducive to performance without taking the risk of straying into "prediction-fiction". In this case, it would be a matter of extracting and using data from wearable devices to identify potential performance indices and then transform them into significant parameters with the ultimate objective of designing a "fair" and "accurate" modeling of running performance. This would be an "intelligent" model capable of taking into account a large amount of information based on physiological factors (e.g., values of critical speed, HR, acceleration, muscle oxygenation, body temperature, hydration rate…), biomechanics (e.g., values of amplitude and frequency of the stride, strength, muscle power, foot placement on the ground…), psychological (e.g., stress indices, motivation, psychological state or personality trait related to the challenge of the competition), environmental (e.g., weather indices, course profile, context of the race…) and technological (e.g., energy storage/return values of shoes, aerodynamic values of textiles) in order to be able to "coach" the athlete at the present time ("T" time), either to indicate to him/her, for example, to accelerate, stabilize or reduce his/her running speed according to the effort he is making and the effort he/she will still have to make with the "ultimate" objective of optimizing sports performance (**Figure 1**). To develop such a formula, we could use, for example, multiple regression to extract and use the relevant data in the model. However, we should be careful about the risk of multicollinearity if one of the explanatory variables in a model is a combination of one or more other explanatory variables in that model, thus distorting the coefficient estimates.

Discussion

The use of connected technologies combined with complex algorithmic methods, such as AI, could offer new perspectives for modeling and/or predicting running performance. However, performance modeling based exclusively on connected data as well as the use of an AI method due to a large amount of data could be relatively limited in relation to:

- The quantity and quality of raw data extracted. How to limit the performance prediction bias related to the precision and/or accuracy of connected devices (46–48)?
- The relevance of some data (i.e., parameters using to qualify or define performance according to existing inter-individual differences between runners or type of race, for example).
- The scientific mastery needed to make sense of the data (e.g., modeling procedure defining the algorithms) (52) and to obtain valid results with respects to the varieties of different algorithmic approaches that can be applied to the same data set (e.g., the ratio used for the data sets of the same size, the ratio used for training and test datasets, the number of hidden layers or the training rate for training a neural network, the number of k in KNN, the type of distance in KNN…) (14, 32, 53, 54)…

Thus, while this perspective of a "connected multifactorial" model seems to be "relatively simple" because data can easily be made public or exploitable *via* databases, it may be sufficiently complicated to model due to several different statistical/algorithmic approaches to integrate to discriminate significant performance factors. So, instinct or calculation? This is the real question that seems to have to be asked before even engaging in modelling (or even prediction) that could tend towards fiction.

Author contributions

LL wrote the first draft. JC helped conceptualize the work and edited and provided further input. All authors contributed to the article and approved the submitted version.

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.

Publisher's note

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High-speed running and sprinting in professional adult soccer: Current thresholds definition, match demands and training strategies. A systematic review

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The aims of this systematic review were (1) to summarize the evidence on absolute velocity thresholds used to classify high-speed running and sprinting, (2) to examine the existing evidence about the individualized thresholds approach, (3) to describe high-speed and sprint running distance match demands, and (4) to provide training strategies for eliciting HSR and sprinting during training sessions in professional adult soccer. This systematic review was conducted following the PRISMA 2020 guidelines. After the authors' screening, 30 studies were included in this review. This review found that, to date, there is no consensus on the absolute thresholds defining high-speed and sprint running in adult soccer players. Until international standards are defined, it is reasonable to set absolute thresholds considering the range of values found in the literature collected in this review. Relative velocity thresholds could be considered for specific training sessions whose goal is to reach near maximal velocity exposure. During official matches, high-speed and sprint running distances ranged from 911 to 1,063 m and 223–307 m, respectively, in professional female soccer players, while ranges from 618 to 1,001 m and 153–295 m, respectively, in professional male soccer players. During training, game-based drills designed in formats using relative areas per player greater than 225 m^2 and 300 m^2 appear to be adequate for achieving high-speed running and sprinting exposure, respectively, for male players. The combination of game-based, running exercises and soccer circuit-based drills is advisable to ensure adequate high-speed and sprint running exposure both at a team and individual level.

KEYWORDS

football, GNSS, GPS, velocity thresholds, team sports, elite sports

Introduction

Soccer is a physically demanding team-sport characterized by an intermittent activity profile with high-intensity activities such as accelerations, decelerations, changes of direction, sprinting, jumping, and tackling interspersed by low-intensity phases of passive (i.e., standing) and active recovery (e.g., walking, jogging) (1, 2). The match play intensity in male soccer has considerably increased over the last 15 years, especially due to the greater high-speed running (HSR) (distance covered at speeds between 19.8 km·h^{-1} and 25.1 km·h^{-1} increased ∼29%) and sprint (distance >25.1 km·h^{-1} increased ∼50%) locomotive demands, which now account for ∼7%–11% and ∼1%–3% relatively to the total distance covered during a match, respectively (2–4). Similarly, intense running in female soccer has increased across various playing positions by approximately 16%–32% from the 2015 to the 2019 *Fédération Internationale de Football Association* (FIFA) World Cup (5). The evolution of soccer matches intensity implies that players should be adequately prepared to cope with the physical demands of the game. Furthermore, HSR and sprint activities are also considered as key determinants for successful performance (6). To illustrate, straight sprinting has been identified as the single most frequent locomotive action preceding goal situations, performed by either the scoring player or the assisting one (7, 8). Moreover, there is evidence highlighting significant positive associations between HSR and sprint distances covered by players in specific positions (e.g., wide midfielders and forwards) and the number of matches won by their team (9). Accordingly, the ability to sustain HSR and sprinting can be considered a key characteristic for soccer players to compete at the professional level (10). Therefore, developing players' capacity to perform HSR and sprinting is paramount for the coaching staff and sport science departments in professional soccer.

In the past, low velocity thresholds (i.e., 14.4 km·h^{-1}–15 km·h^{-1}) were selected to define HSR and sprinting. That was due to the low reliability of wearable micro-technologies such as Global Navigation Satellite Systems (GNSS) and video tracking systems devices available at those times, usually sampling at frequencies lower than 5 Hz (11–13). The advances in these tracking systems have enabled a more accurate quantification of soccer matches and training loads for activities performed at higher velocity (14, 15). At present, the available GNSS technology is deemed valid for measuring distances covered at HSR and peak velocity in sports (16) as well as reliable with excellent inter-unit reliability reported for linear sprint distances [coefficient of variation (CV) = from 1.64% to 2.91%] (17) and sport specific circuits (14). Consequently, tracking technologies are now more commonly used for monitoring HSR and sprinting distances during training and competitions in soccer (18). Despite this widespread use, the current practices among soccer practitioners and sport scientists are not exempt of limitations especially due to the non-standard definitions of HSR and sprinting and the relative velocity thresholds set for their quantification (19). Nowadays, while the official reference thresholds in official competitions of soccer governing organizations such as the *Union of European Football Associations* (UEFA) and the FIFA are 19 km·h^{-1} and 23 km·h^{-1} and 20 km·h^{-1} and 25 km·h^{-1} for HSR and sprinting in women and men, respectively, a large heterogeneity emerges from the scientific literature (5, 20). Therefore, a systematic review that summarizes the evidence on velocity thresholds reference values specifically for professional female and male soccer is needed. The unfolding evidence would facilitate data and knowledge sharing between sport science departments and possibly foster the design of multicentric studies involving clubs from different countries, allowing less uncertain and more robust conclusions to be drawn.

More recently, the use of individual relative thresholds has been proposed as an alternative approach to arbitrary velocity thresholds selection for better quantifying external load measures in soccer (18). For example, in a recent study comparing external loads between starting and non-starting players during a 21-day congested fixture period of a Serie A team, significant between-group differences for sprint distance emerged only when individualized thresholds (i.e., 80% of the maximum peak velocity) were used. This may suggest that the selection of velocity thresholds should account for the individual maximal velocity to accurately quantify sprint distance outcomes during training and matches (21). Nevertheless, given that only preliminary evidence is available on this topic, further research is warranted to investigate the effectiveness of using individual relative thresholds in soccer.

The monitoring of HSR and sprinting distance has been traditionally used to inform training practices with the aim to physically prepare soccer players to the match demands. However, some training contents and drills are unable to elicit HSR or sprinting: summarizing the literature pertaining HSR and sprinting demands and outcomes across different types of exercises can allow practitioners to make evidence-informed decisions when planning training sessions aimed at ensuring adequate HSR and sprint distances exposure.

Therefore, the aims of this systematic review were: (1) to summarize the evidence on velocity thresholds used to classify HSR and sprinting in adult professional female and male soccer players, (2) to examine the existing evidence about the use of individualized thresholds, (3) to describe the HSR and sprinting demands during soccer matches, and (4) to provide training strategies for eliciting HSR and sprinting during training sessions.

Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocols (PRISMA) statement was consulted prior to the start of this review and the checklist completed (22). The review methods were established prior to the conduct of the review (including review question, search strategy and inclusion/exclusion criteria) and no significant deviations from the protocol were made. For this review, an assessment of the risk of bias was not performed since the complexity of judging the quality of observational studies (23).

Search methods for identification of studies

The same systematic search was performed in PubMed (MEDLINE), Web of Science and SPORTDiscus (EBSCO) until October 2022 with no restriction for year of publication. The following search strategy adapted for each database was used: (("football" OR "soccer") AND ("adult" OR "senior")) AND (("high speed" OR "sprint") AND ("running" OR "distance" OR "effort")) AND ((("match" OR "game") AND ("demand" OR "request")) OR ("training" OR "session")) (**Table 1**).

In addition, manual searching, and reference checking have been performed by three independent reviewers (AG, MB and ER) to search other relevant reports.

Inclusion and exclusion criteria

Studies were included if they met the following criteria: (1) original research article; (2) the study was published in English and in a peer-reviewed journal; (3) the research design was either an observational

TABLE 1 Search strategy.

Variable	Search terms
Population	(“football” OR “soccer”) AND (“adult” OR “senior”)
Load	(“high speed” OR “sprint”) AND (“running” OR “distance” OR “effort” OR “velocity”)
Variable	((“match” OR “game”) AND (“demand” OR “request”)) OR (“training” OR “session”)
Final search	Combination of the three groups: “Population” AND “Load” AND “Variable”

study or an intervention study including a control group; (4) participants were professional soccer players of any sex and ≥18 years of age; and (5) the study reported HSR or sprint distances outcomes, defined according to arbitrary or individualized velocity thresholds and collected during official matches or training sessions. Manuscripts were excluded from the review in any of the following cases: (1) sport or football code was different from 11v11 soccer (e.g., American and Australian Football); (2) the subjects played at a lower level of the third national league (if not defined as professional players); (3) metrics reported did not include HSR and sprinting values; (4) GNSS sample frequency used in the study was under 5 Hz, since HSR and sprinting distances have been shown to be less accurate and reliable when tracked with 5 Hz units (12, 13); (5) data came from manual coding.

Data collection and analysis

Two reviewers (AG and MB) independently assessed titles and abstracts of all identified articles, which were downloaded into a web app for systematic reviews (rayyan.qcri.org, Hamad Bin Khalifa University, Qatar) (24). A third independent reviewer was consulted to settle conflict (ER).

Data extraction

Two reviewers (AG and MB) independently extracted data from all relevant articles by reading the articles in full. Key areas of interest were elucidated, and the information extracted included:

- Study population (sample size, gender, competition level and Club’s name when available).
- Number of training sessions or weeks, number of games, number of seasons included in the study.
- High-speed and sprint running metrics, adopted absolute and/or individualized thresholds.
- Details from the study (main findings, average training or match values about physical demand).

Results

Search results

The systematic search through the 3 databases (i.e., Pubmed, Web of Science, SPORTDiscus) produced 823 records, which were screened using a web app for systematic reviews (rayyan.qcri.org, Hamad Bin Khalifa University, Qatar) (24) to remove any duplications. The summary of the systematic search was as follows:

- 697 results on Pubmed
- 76 results on Web of Science
- 50 results on SPORTDiscus

After removing duplicates ($n = 32$), to enable simultaneous screening against the inclusion–exclusion criteria, titles and abstracts were screened to remove articles that were clearly not relevant. At this stage, 753 records were excluded. The full texts of the remaining 38 articles were then accessed for complete screening with 18 studies being excluded as did not meet the inclusion criteria. Ten additional studies were found through other sources, 3 from authors’ archives and 7 following references screening of the 38 articles accessed. Independent screening results were then combined, and any disagreements was resolved by consensus discussion between the authors (AG, MB, and ER). After the final screening, 30 studies were included in this systematic review. The PRISMA flow diagram for the description of the overall process is reported in **Figure 1**.

Descriptive characteristics of the included studies

After final screening, 1 longitudinal observational study and 29 observational studies were included in the systematic review. Data regarding sample size, gender, age, load metrics and results about match and training demand were extracted, verified for accuracy, and reported in **Table 2**.

Four studies were carried out with female players, 25 with male players and 1 with both female and male players. These studies were carried out between 2013 and 2022 and comprised a total of 1,897 participants, divided as follows: 97 adult females and 1,800 adult males. The total number of analyzed games was 442 for females and 2,098 for males. The asymmetry between the number of players and the number of games is due to the different objects of the studies. The male sample takes into account both training monitoring and matches, while the female sample includes only data collected during matches. The total number of pre-season and in-season weeks was 287 overall. The total number of single drills analyzed was 209. The key outcomes of the selected studies in this systematic review included velocity thresholds definition, match demands and training outcomes in terms of HSR and sprint distance.

Discussion

The aims of this systematic review were: (1) to summarize the evidence on velocity thresholds used to classify HSR and sprinting in adult professional female and male soccer players, (2) to examine the existing evidence about the use of individualized thresholds, (3) to describe the HSR and sprinting demands during soccer matches, and (4) to provide training strategies for eliciting HSR and sprinting during training sessions in professional adult soccer. The main findings were: (1) non-standard and a large range of thresholds are used to monitor HSR and sprinting

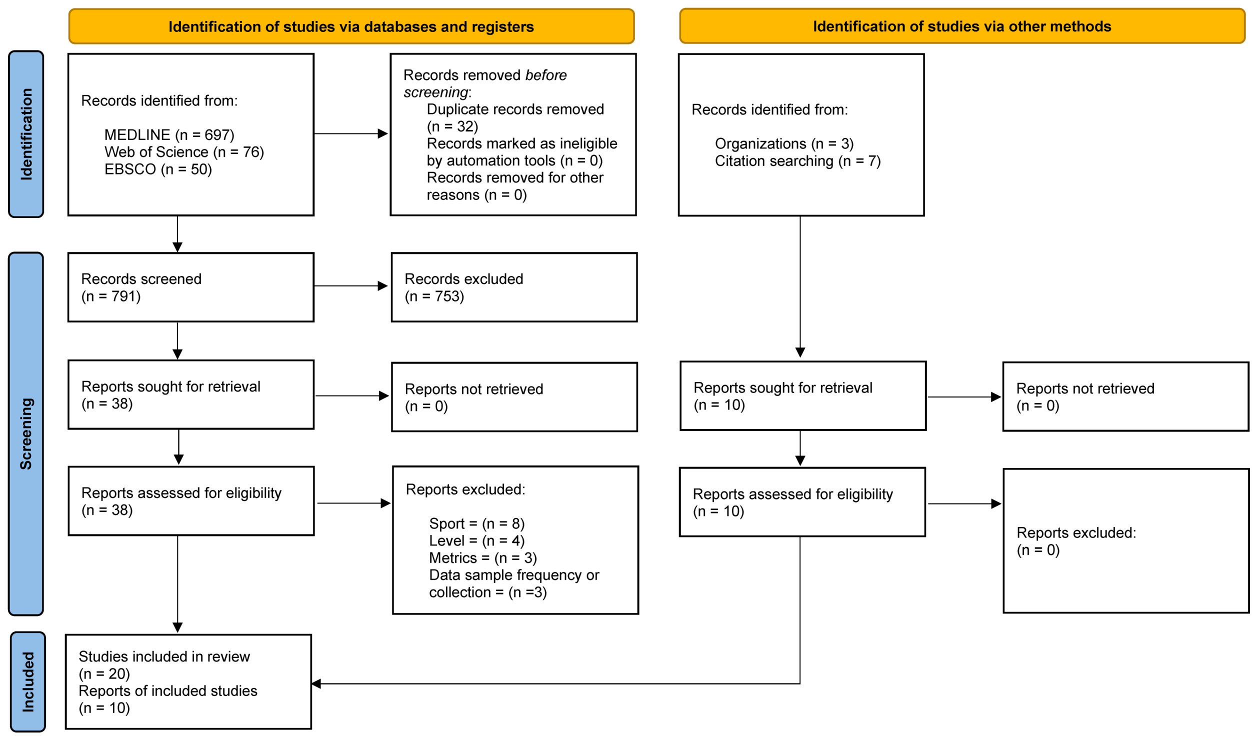

FIGURE 1
PRISMA flow diagram for the description of the overall process.

demands among professional soccer players; (2) absolute and relative thresholds could be used to analyze or compare performances across players and to monitor training at the individual near-to-maximum velocities, respectively; (3) HSR and sprint distances are position-dependent as well as highly variable across the phases of the game; (4) the combination of contextualized game-based and running-based drills should be used to ensure adequate HSR and sprinting exposure during training.

Defining "absolute" thresholds: high, very high and sprint running distance

To date, there is no consensus in the soccer literature about standard thresholds defining zones of running intensities (19). **Figure 2** shows the range of velocity thresholds used in the studies conducted on professional adult female and male soccer players that were included in this systematic review. *High-speed running*, *high-intensity distance* and *high-speed distance* entry velocity are usually set between 12.2 km·h^{-1} and 15.6 km·h^{-1} for females, and between 14.4 km·h^{-1} and 21.1 km·h^{-1} for males, with the most common HSR entry velocity being 12.5 km·h^{-1} and 19.8 km·h^{-1} for female and male, respectively. Similarly, sprint distance entry velocity is commonly set between 17.8 km·h^{-1} and 22.5 km·h^{-1} (22.5 km·h^{-1} was the most common) for females and between 19.8 km·h^{-1} and 30 km·h^{-1} (25.2 km·h^{-1} was the most common) for males. This clearly shows the large variability in velocity for the same external load metrics commonly used among soccer scientists and practitioners.

Two studies used three different thresholds to define running in female soccer: *high-speed*, *very high-speed* (VHSR), and *sprint running* velocity (46, 51). Specifically, Park et al. developed an approach based on logical validity and analysis rigor by using a spectral clustering technique with application of a $\beta = 0.1$ smoothing factor to compute the exact velocity thresholds for the analysis of external load data collected from international female soccer players. The authors were able to define velocity thresholds as follows: HSR $\geq$ 12.5 km·h^{-1}, VHSR $\geq$ 19 km·h^{-1}, sprint $\geq$ 22.5 km·h^{-1} (46). Scott et al. reported the use of the same thresholds based upon the final outcomes in the 30:15 intermittent fitness test (vIFT) in terms of peak velocity reached by the players: HSR $\geq$ 12.5 km·h^{-1} or 60% vIFT (~50% peak velocity), VHSR $\geq$ 19 km·h^{-1} or 80% vIFT (~65% peak velocity), Sprint $\geq$ 22.5 km·h^{-1} or 30% anaerobic speed reserve (~80% peak velocity) (51). The same results coming from these two studies seem to support the robustness of the proposed thresholds for adult female soccer, albeit further investigation is warranted.

Similar to the approach reported above, data mining modeling was proposed to define standard definitions and thresholds for male players by Dwyer and Gabbett 2012. The actual average distribution of velocities was calculated and series of Gaussian normal curves representing four velocity ranges was computed for best fit. The intersecting points for each Gaussian curve were used to determine the velocity range for each of the following locomotive activities: walking, jogging, running and sprinting with the entry velocity for sprinting determined at 21.35 km·h^{-1}. While the conceptual operationalization and the robustness of this approach appear rigorous, the threshold definition emerging from this study could be questioned due to the very low sample

TABLE 2 Summary of studies accompanied by study design, subjects, high-speed running metrics reported and details from the studies.

References	Participants	HSR metrics	Details
Scott et al., 2013 (25) *Observational study*	Professional male soccer players ($n = 15$) Individual training sessions ($n = 97$)	HSR > 14.4 km·h^{-1} VHSR > 19.8 km·h^{-1}	Absolute and % of total distance values recorded during training: HSR = 544 ± 255 m (12.0 ± 3.8%), range 106–1,343 m (4.9–23.3%) VHSR = 132 ± 101 m (2.8 ± 1.9%), range 7–541 m (0.2–8.8%)
Wehbe et al., 2014 (26) *Observational study*	Elite male adult soccer players from Australian-league (A-League) soccer (Sydney Football Club) ($n = 19$) Preseason matches ($n = 8$)	HSR > 19.7 to ≤25.1 km·h^{-1} Sprint > 25.1 km·h^{-1} Putting together thresholds: HIR > 14.3 km·h^{-1} VHIR > 19.7 km·h^{-1}	Positional comparison: midfielders covered 28% more HIR distance than defenders. Match half comparison: HIR and VHIR decreased from the first to the second half by 10 and 11%, respectively. Match status analysis: when the team was winning, average speed was 4% lower than when the team was drawing ($p \leq 0.05$, $d = 0.32$). Pre- and post-goal analysis: scoring or conceding goals did not appear to affect HIR. In the 5-minute intervals before and after a goal was scored, 5-minute HIR distance was 140 and 128 m, respectively ($p = 0.464$). In the 5-minute intervals before and after a goal was conceded, 5-minute HIR distance was 144 and 110 m, respectively ($p = 0.015$). Average and peak 5-minute HIR distance during the whole match was 123 and 237 m, respectively.
Malone et al., 2015 (27) *Observational study*	Professional male players from English Premier League (Liverpool) ($n = 30$) Preseason weeks ($n = 6$) In-season weeks ($n = 36$) Microcycles ($n = 3$)	HSD > 19.8 km·h^{-1}	Higher total distances covered in the early stages of the competitive season and the highest HR response occurring at the midpoint of the season. HSD 1-week in-season microcycles (daily means): early-season = 243 ± 229 m, mid-season = 225 ± 213 m, late-season = 146 ± 104 m. Wide midfielders covered a higher amount of HSD across the different microcycles than central defenders (94 [43–145] m, ES = 0.47 [0.22–0.73], small). Periodization of training load was typically confined to MD-1 (regardless of mesocycle), whereas no differences were apparent during MD-2 to MD-5.
Anderson et al., 2016 (28) *Observational study*	English Premier League male players ($n = 12$) Training sessions ($n = 10$) + matches ($n = 6$) (1-, 2-, 3-game weeks)	HSR = 19.8–25.1 km·h^{-1} Sprint > 25.1 km·h^{-1}	The majority of distance during specific training sessions was completed in the low-to moderate speed zones, whereas the distance completed in high-intensity zones were largely completed in the game itself. HSR: match demand = 706 m; training stimulus = 156 m (1-game week), 192 m (2-game week), 81 m (3-game week). Sprinting: match demand = 295 m; training stimulus = 8 m (1-game week), 16 m (2-game week), 7 m (3-game week).
Carling et al., 2016 (29) *Observational study*	French League 1 male players ($n = 12$) Matches ($n = 31$)	HSR = 19.8–25.2 km·h^{-1} Sprint > 25.2 km·h^{-1} Total HSR (THSR, ≥19.8 km·h^{-1});	Math demand: HSR = 587 ± 133 m; Sprint = 184 ± 87 m; THSR = 770 ± 206 m.
Chmura et al., 2017 (10) *Observational study*	International male soccer players from 32 teams ($n = 340$) Single observations during 2014 World Cup ($n = 905$)	HIR = 19.9–25.2 km·h^{-1} (% of TD) N° of sprints >25.2 km·h^{-1}	The mean distance covered by players at high intensity was 8.83 ± 2.11%. It was significantly longer between the quarter-finals and the semi-finals ($p \leq 0.01$). In the semi-finals the percentage values of TD covered at HI were the greatest. Individually, the greatest percentage achieved was 17% by 2 midfielders. The mean number of sprints performed was 33 ± 11, 1 every 173 s. The greatest number of performed sprints was 68, 1 every 82 s, in a semi-final match. Winning a soccer championship requires players to run longer mean total distances and longer distances at high intensity during a single match.
Mara et al., 2017 (30) *Observational study*	Elite female players from the Australian national league (W-League) ($n = 12$) Matches ($n = 7$)	HSR = 12.24–19.0 km·h^{-1} Sprint > 19 km·h^{-1} High Speed Runs and Sprints (n)	Match demand: HSR = 2,452 ± 636 m; Sprint = 615 ± 258 m; high-speed runs = 376; sprints = 70. A large proportion of high-speed runs (81–84%) and sprints (71–78%) were performed over distances less than 10 m, with 14 s between high-speed runs and 87 s between sprints. The characteristics of high-speed runs and sprints differed between repeat and nonrepeat efforts, and the activity profiles of players varied according to positional groups and period of the match.
Miñano-Espin et al., 2017 (31) *Observational study*	Real Madrid matches ($n = 149$): data from Real Madrid and opposing teams' male players	HIR = 21.1–24.0 km·h^{-1} Sprint > 24 km·h^{-1} High Speed Runs and Sprints (n)	Match demand: HIR distance = 269 m Real Madrid vs. 285 m opposing team; Sprint distance = 245 m vs. 248 m; High Intensity Runs = 11; Sprints = 20. Players from Real Madrid covered shorter distances in HIR and Sprint and executed less sprints than players from the opposing team. No differences were revealed in the HIR and Sprint distances or the number on high intensity runs and sprints performed by players from Real Madrid depending on the quality of the opposition.

(*continued*)

TABLE 2 Continued

References	Participants	HSR metrics	Details
Abbott et al., 2018 (32) *Observational study*	Premier League 2 under 23 professional male players (Brighton and Hove Albion) (*n* = 46) Matches (*n* = 22) LSG, MSG, SSG (*n* = 39)	VHSR = 100% MAS – 30% ASR Sprint >30% ASR Mean and 1-min peak values	Despite eliciting significantly higher average total distances compared with competition, LSGs produced significantly lower peak total distance relative to the competition. For VHSR and sprinting, LSGs elicited similar average intensities to competition; however, peak intensities were significantly lower than competition. VHSR and sprinting distances increased with game format, with LSGs (>7v7) producing the highest intensities. Only LSGs were able to replicate competitive demands, with SSGs and MSGs significantly below competitive values for all positions.
Baptista et al., 2018 (33) *Observational study*	Professional male soccer players (Tromsø Idrettslag) (*n* = 18) Official matches (*n* = 23)	HIR ≥ 19.8 km·h^{-1} Sprint ≥ 25.2 km·h^{-1} Number of HIR and sprint efforts of various length (1–5, 6–10, 11–15, 16–20, 21–25, 26–30, 31–35, 36–40, 41–45, 46–50 m) CoD counts	CB had the lowest values of all positions in both variables but especially pronounced in Sprint (1 m·min^{-1}) when compared with CF (2.5 m·min^{-1}). HIR analysis: CF presented higher values in 26-30 m than all the other positions, while distances of 36–40 and 46–50 m were covered more times by FB. CB were the players with lowest values in these longer distances (36–40 and 46–50). Sprint analysis: CB, FB, CM and WM performed higher number of 1–5 m sprints, while CF covered higher number of 6–10 m sprints. The most common distance covered in HIR for CB, CM, WM and CF was 1–5 m, but for FB was 6–10 m.
Malone et al., 2018 (34) *Longitudinal observational study*	Professional male soccer players (Benfica) (*n* = 37) Weeks (*n* = 48)	HSR > 14.4 km·h^{-1} Sprint > 19.8 km·h^{-1}	When HSR and SR distances are considered independently of aerobic fitness and previous training load history, a U-shaped association exists for distance completed at these speeds and subsequent injury risk. Players with higher aerobic fitness were able to complete increased weekly HSR and SR distances with a reduced injury risk. Higher 21-day chronic sRPE-TL (≥2,584 AU) allow exposure to greater volumes of HSR and SR, which in turn offers a protective effect against injury. 1-week safer zone: HSR = 700–750 m, SR = 200–350 m. Absolute weekly change safer zone: HSR < 100 m, SR < 50 m 3:21 ACWR safer zone: HSR < 0.85, SR = 0.71–0.85
Scott and Lovell, 2018 (35) *Observational study*	International women's soccer players (*n* = 22)	HSR > 12.67 km·h^{-1} (HRDP) VHSR > 17.82 km·h^{-1} (MAS)	In this approach, each players running speed corresponding to HRDP, together with their MAS determined from the VAM-EVAL, were used as the entry-points to the HSR and VHSR zones. Individualised speed thresholds for external load monitoring were not able to better quantify the dose-response of football training during a 21-day training camp in players representing the highest level of women's football. Quantifying the external load using players' peak sprinting speed demonstrated a lower capacity to determine the dose-response of training, with consistently lower associations with heart rate and RPE.
Martín-García et al., 2018 (36) *Observational study*	Professional male soccer players (Barcelona 2nd team) (*n* = 24) Matches (*n* = 37) + training weeks (1 game per week) (*n* = 42)	HSR > 19.8 km·h^{-1} Sprint > 25.2 km·h^{-1}	When comparing starters and non-starters at MD + 1, thanks to the SSG approach used in players with limited game time, non-starters demonstrated greater external loads for TD, HMLD, AMP, ACC, and DEC, but not for HSR or SR. The session that produced the greatest HSR (43%) and SR (45%) distances relative to competition was MD-4. HSR and SR distances are the metrics illustrating the most variability within the microcycle (>80%), which is consistent with the variability found in SSG formats (60–140%), but lower than competition variability (20–30%).
Martín-García et al., 2018 (37) *Observational study*	Professional male soccer players (Barcelona 2nd team) (*n* = 23) Official matches (*n* = 37)	HSR > 19.8 km·h^{-1} Sprint > 25.2 km·h^{-1} 1′, 3′, 5′ and 10′ MIP using TD, HMLD e AMP as the criterion variables	HSR: FB covered the greatest distance, reaching values of 47.2 ± 24.0 m·min^{-1} in the 1′ period. 1′ MIP demand using TD as the criterion variable (positions' average): TD = 191.6 ± 19.7, HSR = 38.3 ± 23.1, Sprint = 10.6 ± 15.6, ACC > 3 m·s^{2} = 2.8 ± 1.6, DEC < −3 m·s^{-2} = 3.5 ± 1.6 1′ MIP demand using HMLD as the criterion variable (positions' average): TD = 173.5 ± 26.0, HSR = 49.9 ± 19.8, Sprint = 16.6 ± 17.4, ACC > 3 m·s^{2} = 3.5 ± 1.7, DEC < −3 m·s^{-2} = 3.6 ± 1.7
Soroka, 2018 (38) *Observational study*	2010 World Cup male players (*n* = 599)	HIR = 19.9–25.2 km·h^{-1} Sprint > 25.2 km·h^{-1}	The largest amount of HIR and Sprint distance was found in midfielders, which did not correspond to studies carried out on players of the Premier League and Primera Division in 2006–2007 (strikers covered the largest sprint distance) (Carling 2008).
Clemente et al., 2019 (39) *Observational study*	Professional male soccer players (Portuguese Second League) (*n* = 23) 5v5 + GK in 40 × 31 m (124 m^{2})	Running = 14–20 km·h^{-1} Sprinting > 20 km·h^{-1}	Greater values for sprinting distance were found in the full match compared to 5vs5 + GK (*d* = 3.673, strong effect), 6vs6 + GK (*d* = 2.606, moderate effect) and 9vs9 + GK (*d* = 1.903, moderate effect) sided games.

(*continued*)

TABLE 2 Continued

References	Participants	HSR metrics	Details
	6v6 + GK in 45 × 32 m (120 m^2) 9v9 + GK in 70 × 50 m (194 m^2)		MSG are not appropriate for simulating the sprinting conditions of official full matches. LSG (9vs9 + GK) simulate official full matches more accurately than the other sided-games that were studied (5vs5 + GK and 6vs6 + GK).
Clemente et al., 2019 (40) *Observational study*	Professional male soccer players (Sporting Lisbona) (n = 27) Training weeks (with 3-4-5 training sessions + 1 game) (n = 22)	RD = 14.0–19.9 km·h^{-1} HSR = 20.0–24.9 km·h^{-1} Sprint > 25.0 km·h^{-1} TMr = Training/Match ratio	It was observed that specific variables (e.g., HSR distance and sprinting distance) were associated with substantially lower ratios than other variables. The TMr for RD and HSR distance were 1.2 ± 0.7 and 1.1 ± 0.8, respectively, in 3-days week and 2.3 ± 1.3 and 2.3 ± 1.5, respectively, in 5-days week. This suggests that the number of training sessions tend to emphasize the stimuli of overall distance and that the demand of three days of training is very similar to the demand of one match. Some determinant external load measures (e.g., HSR or sprinting) are clearly undertrained comparing with more prevalent measures (e.g., TD, ACC or DEC): SSG increase the frequency of ACC/DEC while decreasing opportunities to perform HSR or sprinting.
Dalen et al., 2019 (41) *Observational study*	Male soccer players from an elite Norwegian league team (n = 26) Matches (n = 18) SSGs (28 4vs4 + 28 6vs6) (n = 56)	HIR > 19.8 km·h^{-1} Sprint > 25.2 km·h^{-1}	HIR (m·min^{-1}) in match peak (5 min most demanding period), match mean, 4v4 and 6v6 = 19 ± 3.5, 8.3 ± 2.1, 2.7 ± 0.9, 3.7 ± 2.1. Sprint = 8.8 ± 4, 1.7 ± 0.7, 0.1 ± 0.1, 0.2 ± 0.5. The smaller pitch used for SSGs may lead to a different work pattern from match play, which is supported by the relatively low HIR and sprint distances observed during SSGs in this study. 4vs4 games are a good method of training acceleration and player load tolerance, but SSGs do not represent a good method of training HIR.
Hills et al., 2019 (42) *Observational study*	Championship male soccer players (Hull City Tigers) (n = 17) Matches (35 single observations) (n = 13)	MSR > 14.4 ≤ 19.8 km·h^{-1} HSR > 19.8 ≤ 25.2 km·h^{-1} Sprint > 25.2 km·h^{-1}	Relative TD (+13.4 m·min^{-1}) and HSR (+0.4 m·min^{-1}) distances covered during rewarm-ups increased with proximity to pitch-entry. Very few HSR and no sprint distance were performed during each warmup or rewarm-up bout. Substitutes covered greater TD (+67 to +93 m) and HSR (+14 to +33 m) distances during the first 5 min of match-play versus all subsequent epochs.
Jones et al., 2019 (43) *Observational study*	Professional male soccer players (English Football League One) (n = 37) Matches partitioned in 3 fixture congestion scenarios (n = 79)	HID = 19.9–25.2 km·h^{-1} Sprint > 25.2 km·h^{-1}	The Linear Mixed Model did not identify significant interactions between position, fixture congestion scenario and time period (p = 0.549), position and fixture congestion scenario (p = 0.481), nor fixture congestion scenario and time period (p = 0.162).
Modric et al., 2019 (44) *Observational study*	Professional male soccer players from Croatian Soccer League (6th of 10) (n = 101) Matches (n = 14)	RD = 14.4–19.7 km·h^{-1} HSR = 19.8–25.1 km·h^{-1} Sprint > 25.2 km·h^{-1} InStat technical index	Math demand: HSR = 462 ± 160 m; Sprint = 156 ± 97 m. Association between the running performance of players involved in certain playing positions and overall game performance (InStat index). Specifically, it seems that CD distance in the running zone and number of high-intensity accelerations, FB number of decelerations, and FW sprinting distance are crucial physical requirements of team success.
Oliveira et al., 2019 (45) *Observational study*	Elite male soccer players participating in UEFA Champions League (n = 19) Weeks (n = 39) + matches (n = 50)	HSD > 19 km·h^{-1} Hooper Index	Although there are some significant differences between mesocycles, there was minor variation across the season for the internal and external TL variables used. MD-1 presented a reduction of external TL during in-season match-day-minus training comparison.
Park et al., 2019 (46) *Observational study*	International female players (n = 27) International matches (n = 52)	HSR: ≥ 12.5 km·h^{-1} VHSR ≥ 19 km·h^{-1} Sprint ≥ 22.5 km·h^{-1}	PS in elite women = 29.0 ± 1.5 km·h^{-1} k-means clustering and Gaussian mixture modelling were not appropriate for soccer given the limited instances in which players move at velocities associated with sprinting, which are often considered key physical performance indicators. A spectral Clustering technique with application of a β = 0.1 smoothing factor derived new thresholds featuring both logical validity and analysis rigor. Similar analyses may be warranted to determine appropriate velocity zones for other sports and youth populations.
Rago et al., 2019 (47) *Observational study*	Italian Serie B male soccer players (n = 13)	MSR = arbitrary 14.4–19.8 km·h^{-1} or individualised 80–99% MAS HSR = 19.9–25.1 km·h^{-1} or 100% MAS – 29% ASR Sprint = ≥25.2 km·h^{-1} or ≥30% ASR	Perceptual responses (RPE) were moderately correlated to MSR and HSR quantified using the arbitrary method (p < 0.05; r = 0.53–0.59). However, the magnitude of correlations tended to increase when the individualised method was used (p < 0.05; r = 0.58–0.67). Distance covered by sprinting was moderately correlated to perceptual responses only when the individualised method was used (p < 0.05; 0.55 [0.05; 0.83] and 0.53 [0.02; 0.82]). The magnitude of the relationships between ETL and RPE parameters appear to slightly strengthen when ETL are adjusted to individual fitness capacities, with special emphasis on cardiorespiratory fitness (MAS).

(*continued*)

TABLE 2 Continued

References	Participants	HSR metrics	Details
Ramos et al., 2019 (48) *Observational study*	Under 17 ($n = 14$), Under 20 ($n = 14$) and adult ($n = 17$) international women soccer players	High intensity (HID) = 15.6–20 km·h^{-1} Sprint > 20 km·h^{-1}	Likely to almost certainly differences among all age brackets for the HID and sprint were found (adult > U20 > U17, ES varying from 0.41 [20.23–1.06] to 3.69 [2.63–4.76]), except for the comparison between U17 and U20 for sprint where the differences were rated as unclear. HID: adult (756 m) > U20 (688 m) > U17 (485 m). Sprint: adult (307 m) > U20 (223 m) ≈ U17 (192 m).
Asian-Clemente et al., 2020 (49) *Observational study*	Under 19 professional male soccer players from an elite Spanish first division soccer club ($n = 17$) SSGs (5c5c5 + 2) in 1 single 35 × 35 m pitch or in 2 28.5 × 28.5 m contiguous pitches ($n = 4$)	HSD = 18–21 km·h^{-1} VHSD > 21 km·h^{-1}	VHSD (m·min^{-1}): 2.5 ± 1.8 in 35 × 35 m, 12.8 ± 6.3 using 2 contiguous 28.5 × 28.5 m pitches, 4.6 ± 2.3 in official matches. When soccer is played in smaller relative areas than those used for official games, the ACC and DEC will be increased. Similarly, forcing players to change spaces quickly during SSGs promotes greater running activity, with higher HSD and VHSD covered per player. Although most of the running demands during matches were simulated with the proposed SSGs, it may be necessary to design other types of tasks to train for peak speed and distance covered at sprint speed.
Kelly et al., 2020 (50) *Observational study*	English Premier League male players (Manchester United) ($n = 26$) Entire season ($n = 1$)	HSD > 14.4 km·h^{-1} VHSD = 19.8–25.2 km·h^{-1}	HSD was greater 3 days before a game (MD-3) vs MD-1 (95% CI, 140–336 m) while VHSD was greater on MD-3 and MD-2 than MD-1 (95% CI range, 8–62 m; $p < 0.001$). HSD was similar between mesocycles during the whole season suggesting that training schedules employed in elite soccer may be highly repetitive likely reflecting the nature of the competition demands.
Scott et al., 2020 (51) *Observational study*	Elite female players from National Women's Soccer League (NWSL, United States) ($n = 36$) Match observations ($n = 208$, 11 ± 6 per player)	HSR ≥ 12.5 km·h^{-1} or 60% vIFT (50% PS) VHSR ≥ 19 km·h^{-1} or 80% vIFT (65% PS) Sprint ≥ 22.5 km·h^{-1} or 30% ASR (80% PS)	Subjective ratings of fatigue and wellness are not sensitive to substantial within-player changes in match physical performance. HSR, VHSR, and SR thresholds customized for individual players athletic qualities did not improve the dose-response relationship between external load and wellness ratings. PS in elite women = 30.5 ± 1.8 km·h^{-1} (mean of 5 different roles). Match demand (ABS): HSR = 2,401 ± 454 m; VHSR = 398 ± 143 m; SR = 122 ± 69 m.
Altmann et al., 2021 (52) *Observational study*	German Bundesliga male players ($n = 25$) Match observations ($n = 163$)	HID = 17.0–23.99 km·h^{-1} Sprint ≥ 24.0 km·h^{-1}	CM showed both the largest total (11.66 ± 0.92 km, ES = 0.68–1.86) and HID (1.57 ± 0.83 km, ES = 0.08–0.84) compared to all other positions, WM demonstrated the largest sprinting distance (0.42 ± 0.14 km, ES = 0.34–2.39). Some professional soccer players will likely incur differences in the composition of physical match performance when switching positions and therefore should pay special consideration for such differences in the training and recovery process of these players.
Oliva-Lozano et al., 2022 (53) *Observational study*	Spanish LaLiga male players ($n = 277$) Match observations ($n = 1,252$)	Maximal Intensity Sprint: when an acceleration occurred from 14 km·h^{-1} and the player got to exceed 30 km·h^{-1} for 0.2 s.	Professional soccer players need to be prepared for maximal intensity sprints in the first period of the match as well as maximal intensity sprints under high fatigue conditions given the frequency of sprints in the last period of the match. Training drills should be designed with a special focus on non-linear sprints without possession of the ball, based on the main tactical purpose of each position (e.g., CD: interceptions; CM: recovery runs; FB, WM and FW: run the channel).

ABS, absolute thresholds; ACC, accelerations; ACWR, acute:chronic workload ratio; AMP, average metabolic power; ASR, anaerobic speed reserve [MSS − MAS]; AU, arbitrary units; CB, central backs; CD, central defenders; CF, central forwards; CM, central midfielders; CoD, change of direction; DEC, decelerations; ES, effect size; ETL, external training load; FB, full-backs; FW, forwards; GK, goalkeepers; HID, high-intensity distance; HIR, high-intensity running; HMLD, high metabolic load distance; HR, heart rate; HRDP, heart rate deflection point; HSD, high-speed distance; HSR, high-speed running; LSG, large sided game; MAS, maximal aerobic speed; MD −/+ n, match day minus/plus n days, i.e., n days before/after the match; MIP, maximum intensity period; MSG, medium sided game; MSR, moderate speed running; PS, peak speed; RD, running distance; RPE, rating of perceived exertion; SR, sprint running; sRPE-TL, session rating of perceived exertion training load; SSG, small sided game; TD, total distance; TMr, training/match ratio; UEFA, Union of European Football Associations; VAM-EVAL, a modified version of the Montreal track test; VHSD, very high-speed distance; VHSR, very high-speed running; VHIR, very high-intensity running; vIFT, final velocity of the 30:15 intermittent fitness test; WM, wide midfielder.

analyzed (5 games of 5 players in a professional Australian A-League team), low sample frequency of the GPS units utilized (i.e., 1 Hz), and the lack of evidence suggesting that the velocities within each zone follow a Gaussian distribution (54). To our knowledge no other attempts to establish the rational for the use of "absolute" thresholds on male players were conducted using sufficiently rigorous methods. Therefore, based on the current literature, although these approaches sound promising, the definitions of the thresholds for HSR, VHSR and sprint are still arbitrary (55, 56) with no consensus in the soccer literature (see **Figure 2**).

In addition to the lack of agreement about absolute thresholds to be used, practitioners have to consider that the physical performance level of soccer players continuously improves. For these reasons, it seems desirable for sports scientists to have the capacity to adjust the velocity thresholds and to reprocess the collected data, especially when comparing or sharing data with clubs and federations adopting different numerical references. This approach seems a viable and practical solution at least until consensus on the definition of standard velocity thresholds is achieved. We believe that the establishment of an international standard (by practitioners and manufacturers) may facilitate the data exchange between clubs and national teams, which in turn could increase the value of velocity monitoring in soccer. We suggest that technology providers allow practitioners to set their absolute thresholds (this is indispensable for comparisons with historical data owned by the club) and to provide default international standardized thresholds, which could be used to share data with other clubs or national teams. Even if this is achieved, practitioners need to be aware that some limitations in accuracy and reliability exist between tracking technologies (e.g., between GNSS brands), therefore caution is needed when data from different clubs (that use different devices) are compared (57).

Relative velocity thresholds

The use of individualized thresholds quantifying internal load measures [i.e., heart rate, maximum oxygen consumption (VO_{2max})] can facilitate training prescription and monitoring by setting relative work intensities corresponding to individual physiological targets (58). For example, coaches and sport scientists can tailor the training plans based on well-defined physiological parameters such as VO_{2max}, maximum heart rate and onset of blood lactate accumulation (OBLA) (59). What has just been described above could also be used for the evaluation of individual external load parameters such as running velocity. The rationale of implementing relative thresholds for velocity parameters is justified by the assumption that absolute thresholds fail to account for the players' individual physical capacities, and therefore, they could result in an inappropriate assessment of the players' external load performed during training (21) and matches (55). Practitioners should consider that players have specific physical characteristics (e.g., peak velocity) that should be accounted for during the monitoring of training and matches. The use of relative individual thresholds would allow for more precise programming of the training load, which could help to design the appropriate dose of HSR and sprinting distance, preventing the implementation of unattainable velocities that could potentially be injurious (60), or not high enough to elicit the desired adaptation (61, 62).

Previous research has tried to individualize specific velocity thresholds based on physiological or performance parameters using some tests, which have been summarized in this review. HSR was defined as the velocity corresponding to the VO_{2max} [maximal aerobic speed (MAS)] in both women (63) and men (47), which was assessed through gas analysis methods during an incremental ramp test or the final velocity reached during the Yo-Yo Intermittent Recovery Test level 1 (64, 65). Alternatively, HSR threshold was set at the velocity corresponding to the heart rate deflection point determined from an incremental field test in women (35) or from a different incremental field test in men (60). When considering players' physical and fitness attributes, sprint entry velocity was defined as the velocity corresponding to the MAS determined from an incremental field test in female players (35), or as the value ≥30% of the anaerobic speed reserve, calculated as the difference between maximal sprint velocity and MAS in male players (47). For further details about maximal sprint speed and anaerobic speed reserve definition, the reader is invited to refer to the article of Buchheit and Laursen (66) and Sandford et al. (67).

Nevertheless, the validity criterions underpinning the determination of individual velocity thresholds using physiological parameters collected during continuous test protocols rather than external load proxies fail to consider the intermittent and repeated accelerative profile, which is typical of soccer (68), and as such seems inappropriate or at least inaccurate.

In contrast with the physiological approaches reported above, another common method to define relative thresholds from measures of external load is the percentage of the individual peak velocity, measured as the maximal velocity attainable during an all-out effort (69). Using this rationale, sprint running entry velocity was set at 80%–85% of peak velocity reached in a >30 m sprint test in female players (63) and at 80% of peak velocity reached in a 40 m sprint test in male players (60). In another study, sprint threshold was set either at >80%, >85% or >90% of the highest running velocity measured during either training sessions or matches (70). To date, the most reliable and simplest procedure to determine the peak velocity is through GNSS systems during a 40 meters sprint test (18, 63, 69). Alternatively, peak velocity can be tracked and determined from official matches (71), although this approach is not exempt from limitations due to the fact that players do not necessarily always reach maximal velocities during matches due to the contextual constraints and their specific positional demands (18, 69). In official matches some between-gender differences were observed for sprint velocities with 30.5 ± 1.8 km·h^{-1} (mean of 5 different roles) (51) and 32.0 ± 1.0 km·h^{-1} (mean of 3 different roles) (72) for female and male players, respectively. In consideration of the accuracy and reliability of tracking devices (14) now easily affordable and widely available, it would be reasonable to perform, at the beginning of a training session and after a standardized warm-up procedure, an all-out 30–40 m sprint test as a valid, high ecological and time-efficient approach to determine peak velocity for every player, whereby individual velocity thresholds could then be defined.

Although the number of studies that support the concurrent validity of the use of individualized thresholds are limited, we still have some evidence, specifically previous studies have reported the association between internal load and HSR demands. The perceptual responses (RPE using Borg's category ratio scale - CR10) provided by soccer players (Italian Serie B) at the end of the match were moderately correlated ($r = 0.53$–0.59) to distance covered expressed using absolute velocity thresholds ranging between 14.4 and 19.8 km·h^{-1} and HSR (>19.8 km·h^{-1}) (47). Notably, the strength of the correlations tended to increase, albeit not significantly, when individualized velocity thresholds were used ($r = 0.58$–0.67) (47). Moreover, distance covered by sprinting was moderately correlated to RPE only when an individualized threshold was used ($r = 0.55$) (47). In contrast, the use of individualized velocity thresholds were not able to better quantify the dose-response of female soccer players during a 21-day training camp (35). This study reported that the quantification of the external load using players' peak sprinting velocity demonstrated a lower capacity to determine the dose-response of training, with consistently lower associations with heart rate and RPE (35). In another study, HSR and sprinting thresholds customized for individual female players athletic qualities did not improve the dose-response relationship between external load and wellness ratings (51). In

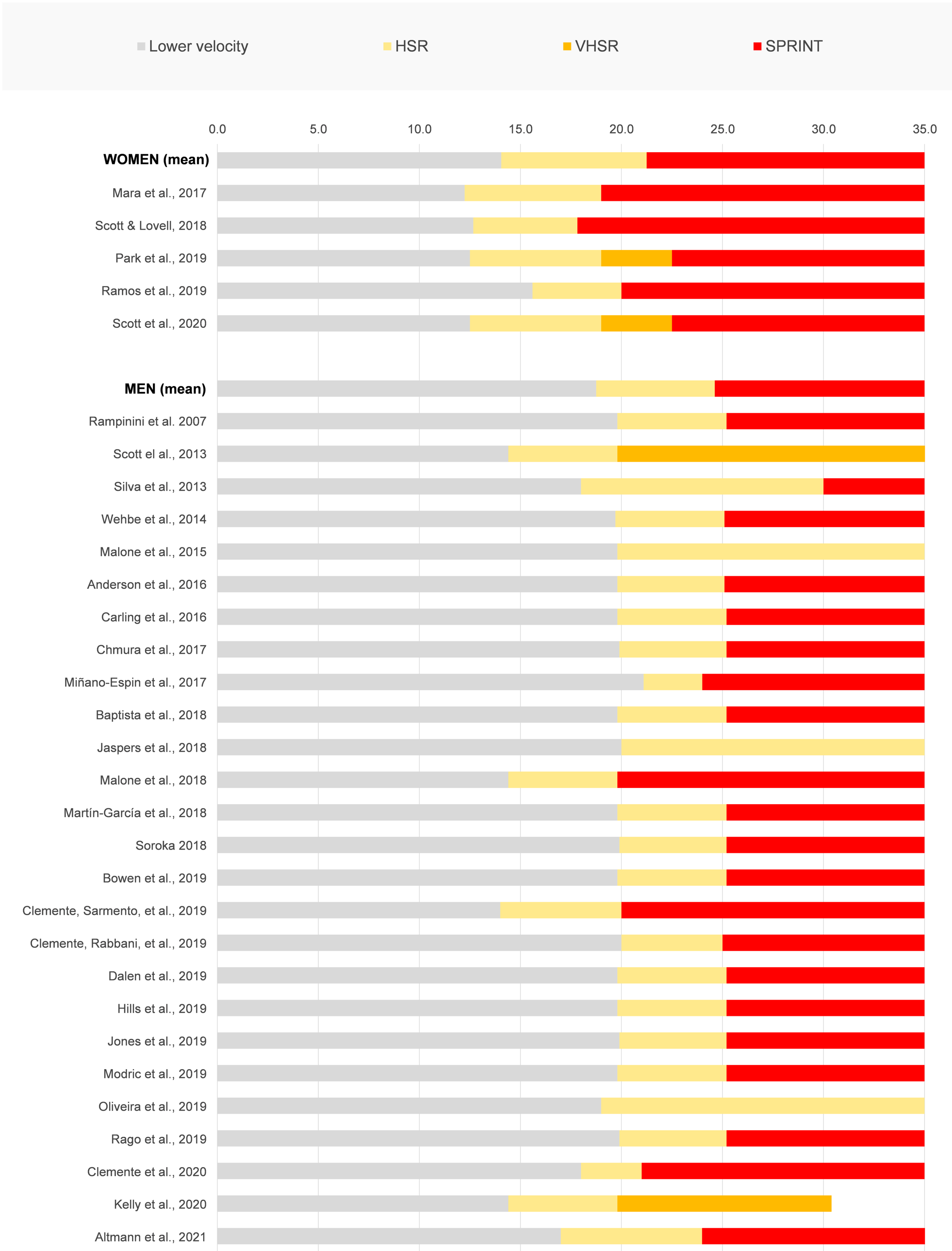

FIGURE 2
High-speed running (HSR), very high-speed running (VHSR) and sprint thresholds for elite adult female and male soccer players expressed in km·h^{-1}.

summary, the individualization of velocity parameters based on players' individual fitness level (i.e., MAS or peak velocity) only marginally improves (trivial or small magnitude of the change) relationships between external and internal training load parameters (35, 47, 51). Based on the evidence reported so far, it is possible to confirm that internal and external training load parameters, independently by the use of absolute and relative thresholds, are different constructs and for this reason practitioners should monitor both.

The current evidence does not allow us to make definitive conclusions about the use of individualized velocity thresholds in soccer. While the use of individualized thresholds seems to offer the advantage of a more precise quantification of the individual external load, it may preclude comparisons between players, between training sessions and matches or within time when the same players have changed their individual velocity thresholds (73). In our opinion, either absolute or relative velocity thresholds seem appropriate to monitor HSR and sprinting exposure in professional soccer players. While absolute values are suitable to make between-player comparisons, relative thresholds are preferable for the individualization of the high-velocity aspects of the external training load. However, more research is needed on this topic before recommending the use of one over the other.

High-speed running and sprinting during official matches

A summary of HSR and sprinting distance outcomes and related velocity thresholds during matches among professional adult female and male soccer players is reported in **Table 3**. HSR (>15.6 km·h^{-1}) and sprint (>20 km·h^{-1}) demands in professional female soccer were around 1,000 m (range: 911–1,063 m, 10.1–11.8 m·min^{-1}) and 270 m (range: 223–307 m, 2.5–3.4 m·min^{-1}), respectively. In professional male soccer players, the analogous outcomes for HSR (>19.8 km·h^{-1}) and sprint (>25.1 km·h^{-1}) demands were around 760 m (range: 618–1,001 m, 6.9–11.1 m·min^{-1}) and 200 m (range: 153–295 m, 1.7–3.3 m·min^{-1}).

Female soccer players perform a large proportion of high-speed runs (12.24–19.0 km·h^{-1}) and sprints (>19.0 km·h^{-1}) over distances shorter than 10 m (81%–84% and 71%–78%, respectively), with an average recovery time of 14 s between high-speed runs and 87 s between sprints, i.e., a 1:7 and 1:43 work to rest ratio, respectively (30). Similarly, in professional male players the most common distance covered in HSR (≥19.8 km·h^{-1}) was 1–5 m, apart from the full backs who covered average HSR runs between 6 and 10 m (33).

Practitioners need to consider that the between-match variability for HSR (19.8–25.2 km·h^{-1}) and sprint (>25.2 km·h^{-1}) distances is notably high and is affected by the positional role (29, 52). Higher variability has been reported for central players (midfielders and defenders) while lower variability for wide midfielders and attackers (29, 74, 75). For example, the CV for female players ranged between 28% and 41% for HSR (>16.3 km·h^{-1}) and between 35% and 65% for sprint (>20.0 km·h^{-1}) distance (74). In male professional players, the CV for HSR and sprint ranged between 16% and 18% and between 31% and 37% respectively (29, 75). Moreover, the characteristics of HSR and sprints differed between positional roles and period of the match (30). In the 2010 World Cup, the largest amount of HSR (19.9–25.2 km·h^{-1}) and sprint (>25.2 km·h^{-1}) distance was observed in midfielders (38), which did not completely reflect the outcomes of previous studies conducted in the English Premier League and Spanish Primera Division in 2006–2007, where strikers were found to cover the largest sprint distances (76). In addition, practitioners should consider that the main tactical purpose of each playing position influence how the player has to perform maximal intensity sprints: interceptions for central defenders, recovery runs, closing down and pressing for midfielders, running in the channel to receive/exploit space, break into the box, or run-in-behind for wide-midfielders and forwards (53). Moreover, when conducting a contextual analysis of the physical demand during matches, HSR and sprinting seem to be affected by the quality of the opposition, with increasing values reported during matches played against stronger than weaker opponents (72). Moreover, a further level of contextualization requires interpreting these findings in

TABLE 3 High-speed running (HSR) and sprint match demands for elite adult female and male soccer players.

Studies	Subjects	HSR		Sprint	
Mara et al. 2017	Women – Elite Australian	*12.2–19 km·h^{-1}*	2,452 m	*>19 km·h^{-1}*	615 m
Scott et al. 2020	Women – Elite United States	*≥12.5 km·h^{-1}*	2,401 m	*≥22.5 km·h^{-1}*	122 m
Ramos et al. 2019	Women – Adult	*15.6–20 km·h^{-1}*	**756 m**	*>20 km·h^{-1}*	**307 m**
Ramos et al. 2019	Women – U20	*15.6–20 km·h^{-1}*	**688 m**	*>20 km·h^{-1}*	**223 m**
Anderson et al. 2016	Men – Premier League	*19.8–25.1 km·h^{-1}*	**706 m**	*>25.1 km·h^{-1}*	**295 m**
Modric et al. 2019	Men – Elite Croatian	*19.8–25.1 km·h^{-1}*	**462 m**	*>25.1 km·h^{-1}*	**156 m**
Carling et al. 2016	Men – League 1	*19.8–25.2 km·h^{-1}*	**587 m**	*>25.2 km·h^{-1}*	**184 m**
Kelly et al. 2020	Men – Premier League	*19.8–25.2 km·h^{-1}*	620 m	–	–
Miñano-Espin et al. 2017	Men – La Liga	*21.1–24.0 km·h^{-1}*	277 m	*>24 km·h^{-1}*	247 m
Wehbe et al. 2014	Men – Elite Australian	*>19.7 km·h^{-1}*	**645 m**	–	–
Baptista et al. 2018	Men – Elite Norwegian	*≥19.8 km·h^{-1}*	**744 m**		
Rampinini et al. 2007	Men – League 1	*>19.8 km·h^{-1}*	**821 m**	–	–
Stevens et al. 2017	Men – Eredivisie	*>19.8 km·h^{-1}*	**738 m**		
Dalen et al. 2019	Men – Elite Norwegian	*>19.8 km·h^{-1}*	**747 m**	*>25.2 km·h^{-1}*	**153 m**
Clemente et al. 2019	Men – Dutch and Spanish 2nd Division	*>20 km·h^{-1}*	**730 m**		
Asian-Clemente et al. 2020	Men – U19 elite Spanish	*>21 km·h^{-1}*	414 m	–	–
Altmann et al. 2021	Men – Bundesliga	*17.0–23.99 km·h^{-1}*	1,340 m	*≥24 km·h^{-1}*	495 m

Data are grouped by HSR zone to facilitate between-studies comparison. Bold values were considered for mean match demand calculation reported in the text.

consideration of the result of the game. In fact, independently from the opponents' level, it seems that soccer players perform significantly less high-intensity activity (21.1–24.0 km·h^{-1}) when winning than when losing or when the score is balanced (31). This may be the main reason why no differences were found in the distances covered by players of Real Madrid (that won during the explored period approximately 70% of the total matches played) depending on the strength of the opposing team (31). Another common scenario in professional soccer and worthy of consideration pertains to fixture congestion. From preliminary results, it seems that playing many consecutive games does not affect the amount of HSR (19.9–25.2 km·h^{-1}) covered during the consecutive matches (43), although the flawed methodological approach to quantify HSR exposure across studies investigating this area precludes to make definitive conclusions (77).

Considering the average match demands as the only reference could mislead strategies aiming at physically preparing players during training. In 2014 World Cup, the mean HSR (19.9–25.2 km·h^{-1}) distance covered across all positions was 8.8% ± 2.1% of the total distance, but with midfielders peaking at roughly 17% (10). Interestingly, relying upon the most intense periods of the game, relevant consideration for training prescription can unfold. For example, the mean and peak HSR distances (>14.3 km·h^{-1}; 24.6 and 47.4 m·min^{-1}, respectively) doubled when considering 5-min epochs in Australian-league soccer (26). In Norwegian players, HSR (>19.8 km·h^{-1}) and sprinting (>25.2 km·h^{-1}) in the most demanding 5-min epochs reached 19 ± 3.5 and 8.8 ± 4 m·min^{-1} respectively, while the match mean reported in the same study was 8.3 ± 2.1 and 1.7 ± 0.7 m·min^{-1}, respectively (41). In the Spanish La Liga, analyzing high-metabolic demands by using 1-min epochs revealed 49.9 ± 19.8 and 16.6 ± 17.4 m·min^{-1} for HSR (>19.8 km·h^{-1}) and sprinting (>25.2 km·h^{-1}), respectively (37). In view of these reference values, it sems reasonable to consider higher benchmark values to not underestimate the real exercise intensity during matches or when planning the prescription of training drills aiming at exposing soccer players to HSR and sprint distances. However, practitioners should consider that the "maximal intensity period" is a complex and composite construct reflecting an extreme internal response elicited *via* various combinations of physical and contextual factors. To note, this demands do not occur concurrently during the game and similarly for all metrics and players (78), thus a more accurate analysis of "maximal intensity period" requires a case-by-case approach.

High-speed running and sprinting during training

High-speed running and sprinting distances are the metrics with the highest variability observed across days during the weekly training microcycle (between 60%–120%), and higher as compared to official matches (between 20%–30%) (36). This variability is reasonably a consequence of the weekly plan that requires a day-by-day load modulation and especially the unpredictable fluctuating nature of game-based drills such as sided-games. These findings may partially occur due to specific and different positional demands which are exacerbated during game-based training drills. Therefore, game-based drills should be implemented in combination with other forms of training to mitigate the large variability in terms of HSR and sprinting. Moreover, individual HSR and sprinting cumulative distances and frequency should be monitored to ensure effective load management strategies, especially to avoid detraining for those players less taxed during the game.

Knowledge of the match physical demands allows for the development of appropriate prescription of the training load as to adequately prepare individual players. Summaries from studies involving elite (40, 45, 79, 80) and sub-elite professional players (36, 81) revealed that for total distance and accelerations the training to match ratios tend to vary from ∼1 to 4 arbitrary units (AU) (that means in 1 week of training players were exposed to 1–4 times the match-load), with the exceptions of the ratios for HSR and sprinting distance, which were relatively lower and clearly under-attained during the training week compared to other measures such as total distance and accelerations (see **Table 4**). For HSR the training to match ratio was reported to vary between 0.2 AU and 2.3 AU, while for sprinting the values ranged from 0.03 AU (i.e., trivial sprinting exposure during training) to 1.3 AU. Remarkably, these ratios are average team values, which in consideration of the large inter-subject variability observed for the same external load metrics should be interpreted with caution.

In view of the current evidence, particular attention should be directed towards non-starting players as recent studies conducted in the Italian Serie A and the English Premier League revealed that non-starting players were exposed to considerable lower HSR and sprinting distances as compared with starting players (21, 82). Accordingly, it seems reasonable that dedicated compensatory drills targeting HSR and sprinting should be implemented during training to compensate for the lack of match related HSR and sprint running exposure and to avoid detraining. To design specific sprint training drills, playing position and contextual variables should be considered, for instance, defenders usually sprint to intercept the ball, midfielders run to close down and press the opponents, and attackers run throughout the channel to receive/exploit space and break into the box (53).

When soccer players use smaller relative areas during training compared with those used for official games, the number of accelerations and decelerations increase, but it is difficult to achieve adequate volumes of HSR (83). For instance, matches are played on a 105 × 68 m pitch (i.e., 357 m^2 per player) that allow for an HSR distance of 8.4 m·min^{-1} and sprinting distance of 2.2 m·min^{-1}, while during SSG 4v4 using a pitch of 39 × 39 m (i.e., 190 m^2 per player), the HSR distance is of 2.7 ± 0.9 m·min^{-1} and sprinting distance of 0.1 ± 0.1 m·min^{-1}, and during medium sided games (6v6) played on pitch of 47 × 43 m (i.e., 168 m^2 per player) the HSR distance is 3.7 ± 2.1 m·min^{-1} and sprinting distance of 0.2 ± 0.5 m·min^{-1} (41). Instead, sided-games designed as large formats and with relative areas per player greater than 225 m^2 and 300 m^2 seem adequate to induce HSR and sprint distances, respectively, comparable to the analogous match external load outcomes (84). However, it is worth noting that the uncontrolled and unpredictable nature of game-based approaches may still cause large variability across players with the risk of overexposure to some and underexposing to others.

TABLE 4 Training/Match ratio (T/M ratio) for high-speed running (HSR) and sprint in adult male soccer players.

Reference	Subjects	HSR weekly load				Sprint weekly load			
		Thresholds	Training	Match	T/M ratio	Thresholds	Training	Match	T/M ratio
Anderson et al. 2016	Men – Premier League	*19.8–25.1 km·h^{-1}*	156	706	0.2	*>25.1 km·h^{-1}*	8	295	0.03
Kelly et al. 2020	Men – Premier League	*19.8–25.2 km·h^{-1}*	987	620	1.6				
Clemente, Rabbani et al. 2019	Men – Elite Portuguese	*20–24.9 km·h^{-1}*	–	–	2.3				
Stevens et al. 2017	Men – Eredivisie	*>19.8 km·h^{-1}*	811	738	1.1				
Martin Garcia et al. 2018	Men – La Liga - Reserve	*>19.8 km·h^{-1}*	726	440	1.7	*>25.2 km·h^{-1}*	131	100	1.3
Baptista et al. 2018	Men – Elite Norwegian	*≥19.8 km·h^{-1}*	460	744	0.6	*≥25.2 km·h^{-1}*	69	144	0.5
Clemente, Owen et al. 2019	Men – Dutch and Spanish 2nd Division	*>20 km·h^{-1}*	1,342	730	1.8				

Only data referred to weeks within 4 or 5 training days + 1 match day are reported. Data are grouped by HSR zone to facilitate between-studies comparison

An alternative or complementary training method to sided-games to induce HSR and sprinting exposure are running-based drills with linear and non-linear sprints. Again, starting from the performance model defined by the game, strength and conditioning coaches should consider that the mean sprint (>30 km·h^{-1}) duration recorded in LaLiga players ranged from 5 to 9 s, with a mean distance covered ranging from 30 to 55 m (53). Mixing linear sprints and sided-games, Ade and colleagues implemented repeated runs lasting 15 s and performed by young under 19 soccer players immediately before and after a sided-games bouts to ensure adequate coverage of distances above 19.8 km·h^{-1} (85, 86). In under 19 elite male players, asking players to change zone of the pitch quickly during small sided-games promoted higher HSR covered per minute. These authors compared a ball possession drill played in a single pitch (35 × 35 m pitch) to a drill with 2 contiguous pitches (28.5 × 28.5 m each), and they found that HSR was 2.5 ± 1.8 m·min^{-1} in the single pitch (i.e., 72 m^2 per player) and 12.8 ± 6.3 m·min^{-1} using 2 contiguous pitches, while during official matches was 4.6 ± 2.3 m·min^{-1} (49). Another option to perform HSR and sprinting distance is to use isolated running-based drills or adding running phases during sided-games. In this case, HSR and sprint running exposure can be accurately prescribed and controlled with a lower degree of uncertainty given that the running intensity is predetermined, fixed, and easily monitored.

More recently, a game profile-based training (GPBT) approach has been proposed to induce relative HSR and sprint running distances comparable or greater than matches outcomes in under 19 elite male soccer players (87). A GPBT could be defined as 1 or more bouts of physical and technical activities (e.g., high-intensity intermittent running, changes of direction, and passes), which replicate the type of movements and physical demands (e.g., internal and external loads) of match-play (88). It was reported that a GPBT was more demanding in terms of distance run above 19 and 25.2 km·h^{-1} compared with a 5v5 small sided-game in a 42 × 30 m pitch (i.e., 126 m^2 per player), specifically, 10.2 m·min^{-1} during GPBT vs. 4.6 m·min^{-1} during small sided-game for HSR and 4.2 vs. 2.0 m·min^{-1} for sprinting (87). Moreover, beneficial chronic effects on linear sprinting capabilities over 10 m and 20 m were found following a 8-week training period including GPBT, with greater improvements compared to sided-games training in the form of 5-a-side formats. While generalizing such findings to other cohorts warrants caution, the nature of the GPBT drills as fixed running circuits entailing intermittent phases of walking, jogging, running and sprinting may presume that similar outputs can be expected among adult female or male soccer players as well.

Another aspect to be considered when preparing players for HSR and sprint running game demand is sprinting in fatigue condition, since maximal intensity sprints were reported to be more frequent in the first, but also in the last, 15 min of the match, regardless of the playing position (53). Training HSR and sprint running at the end of the training session should therefore be taken into consideration even if a higher risk of musculoskeletal injury is conceivable.

In summary, practitioners are recommended to use a combination of adapted sided-games, GPBT, and running-based drills to ensure adequate HSR and sprint running exposure to their players during training. HSR and sprinting exposition are particularly important for non-starting players that need to compensate for missing the speed load exposition of the match, which often demands near-to-maximal velocity efforts (21, 82).

Limitations and future directions

A number of limitations should be acknowledged in regard to this review: (1) inclusion of studies published in English only, which may have excluded relevant evidence on the topic coming from other languages; (2) some possible methodological issues (e.g., statistical power and confidence in the result) could arise because some studies have a relatively small sample size, while only 5 out of 30 studies included a large cohort; (3) only 5 out of 30 studies involved female professional players, mainly due to the lower diffusion of soccer among women; (4) this study did not analyze in depth the effect of technical and tactical factors on HSR and sprint demands during matches; (5) considering that the training information (related to HSR and sprint demands) reported in this review comes from studies that have mainly enrolled youth players instead of senior players (i.e., first-team players), this study cannot fully generalize the main findings to adult professional cohorts. As such, future studies should address these limitations and focus their attention on the monitoring of HSR and sprint demands during training among adult male and female (who are particularly underrepresented in the extant literature) professional players.

Practical applications

Since there is no consensus on a specific absolute threshold defining high-speed running and sprint in adult female and male soccer players, and currently an international standard for such velocity thresholds does not exist, practitioners could set as entry velocity for HSR and sprinting values included in the range suggested from this review. A second option for practitioners is to use the velocity thresholds (HSR and sprint) adopted by FIFA and UEFA such as 19 km·h^{-1} and 23 km·h^{-1} for female and 20 km·h^{-1} and 25 km·h^{-1} for male.

Beyond absolute velocity thresholds, relative thresholds should be considered for specific training sessions where the goal is to reach near to maximal velocity exposure accounting for players' individual physical velocity capacity.

When analyzing the match demand, practitioners should consider that HSR and sprint distances are position-dependent as well as highly variable across the phases of the game and between the games: using HSR and sprint distance as performance indicators could introduce bias if not contextualized. In any case, players have to be ready for HSR and sprinting: to train the HSR and sprinting game demand, practitioners could use a combination of adapted sided-games, GPBT, and running-based drills to ensure adequate HSR and sprint running exposure to their players during training. Finally, monitoring HSR and sprint distances during every single session can allow the practitioner to verify the validity of the training process and optimize physical development, which is necessary to carry out the most demanding phases of the game, which require velocities close to the maximum (e.g., during high-speed counterattack).

Author contributions

AG: was responsible for the original idea of the manuscript and performed the literature search. AG, ER and MB: performed the reference selection. AG: wrote the first draft. All authors contributed to the article and approved the submitted version.

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.

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External and internal training load comparison between sided-game drills in professional soccer

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This study aims to quantify and compare the external and internal training load demands of sided-game drills in professional team players during the competitive season. Twenty-four male professional soccer players of the same club were enrolled in this study. Drills were categorized as large-sided games (LSG): 10vs10 (84 × 60 m or 72 × 60 m), Hexagon possession 9vs9 + 3 (36 × 48 m), Possession gate 8vs8 + 2 (36 × 44 m), Possession 7vs7 + 3 (30 × 32 m) or as Small-sided games (SSG): 6vs6 (48 × 42 m), and Possession 6vs4 (30 × 60 m). A total of 7 drills and 279 individual data points were included in this analysis. Distance covered, high-speed running (HSR), and sprinting distance were all calculated in meters per minute (m.min^{-1}) while total accelerations (>3 m.s^{-2}) and total decelerations (– < 3 m.s^{-2}) were calculated in number of actions per minute (n.min^{-1}). All external load was measured with global navigation satellite systems (GNSS) STATSports Apex units. Players' internal load was quantified using their rating of perceived exertion (RPE). We found that distance covered ($p < 0.01$, *large*), HSR ($p < 0.01$, *large*), and sprinting distance ($p < 0.01$, *large*) changed between drills (e.g., greater in LSG formats), acceleration ($p < 0.01$, *large*) and deceleration ($p < 0.01$, *large*) demands were greater in smaller formats (e.g., SSG 6vs6, and Possession 6vs4), while RPE was lower in the Possession gate 8vs8 + 2 format ($p < 0.01$, *large*). This study found that sided-games can replicate and sometimes exceed some match-specific intensity parameters, however, HSR and sprinting were consistently lower compared to official matches.

KEYWORDS
football, team sports, performance, GPS, monitoring

Introduction

Soccer requires players to have a high level of fitness to consistently execute the technical and tactical demands of the game (1, 2). The appropriate combination of these three factors in the training process plays a paramount role in short- and long-term preparation for competition (3, 4). Sided-games are a common form of training used to enhance performance and prepare players in professional soccer (5, 6). Coaches use sided-game drills that vary in pitch size, rules and in number of players to develop the physical (*e.g.*, aerobic fitness, speed), psychological, technical and tactical (*e.g.*, possession skills, pressing) skills needed in soccer (7). Although sided-games are commonplace in training, the application of such drills may insufficiently replicate the physical demands of the game (8).

It is important for coaches and sport scientists to track the external and internal demands of training to enhance physical capacity (3, 9). External load is commonly monitored using global navigation satellite system (GNSS) units across elite and semi-professional soccer teams (10–12). GNSS units acquire and track multiple satellite systems (e.g., Global Positioning System, GLONASS) and have evolved to provide practitioners with a more accurate and holistic understanding of the demands placed upon soccer players (10, 13). In addition to the monitoring of distance and velocity data, GNSS units have an integrated triaxial accelerometer (e.g., acquisition frequency usually of 100 Hz) that allows for evaluation of additional accelerometer-based parameters (14). Specifically, practitioners often assess acceleration and deceleration efforts (considered above a threshold of >3 $m.s^{-2}$ and <−3 $m.s^{-2}$, respectively) during training and competition (15). The analysis of external training load can be implemented alongside the monitoring of internal training load parameters such as heart rate, blood lactate, and the player's rating of perceived exertion (RPE) (16, 17). However, the daily recording of heart rate and blood lactate remains challenging, while the use of RPE is non-invasive, cheaper, and easier to implement (16). The construct validity of RPE has been reported in several studies and was found to be strongly correlated with heart rate ($r = 0.74$) and blood lactate ($r = 0.83$) during aerobic exercise (4, 18). For these reasons, RPE can give an overall indication of a players' internal load (18).

The monitoring of both external (e.g., distance, high-speed running [HSR], accelerations, decelerations) and internal load (e.g., RPE) parameters and the consequent manipulations of training variables (sided-games rules and spaces) play a key role in players' fitness development throughout the season and for players' readiness for competition (3, 17, 19). Sided-games in soccer have received a lot of scientific interest and support throughout the years because of their ability to achieve adequate internal load demands (*i.e.,* around 85%–90% of maximum heart rate) and stimulate aerobic fitness amongst soccer players (5–7). Additionally, sided games are attractive to coaches because they offer a large variety of challenges and enable players to train certain technical aspects and tactical principles in greater detail. Coaches also manipulate the objectives of games (possession or goal-oriented) and vary rules (goal size, presence of neutral players, or numerical player overloads) to achieve different psychophysical (*e.g.*, RPE, heart rate) and mechanical load (*e.g.,* accelerations) objectives and stimuli (7, 15). However, a recent systematic review by Dello Iacono et al. (8), reported that sided-games (ranging from small to large) are inadequate for training the higher speed demands of the game. Specifically, sided-games consistently offered a lower dose of high-speed running and sprinting distance (per unit of time) compared to official matches (8).

Further investigation is necessary to better understand whether sided-games formats (with different rules and objectives) elicit a similar training load as well as it is needed to verify if the sided games used with professional players in an ecological context can replicate the physical demands of regular matches. Therefore, the aim of this study was to quantify and compare the external and internal training load demands of sided-game drills in professional team players during the official season. We aimed to verify, first, if different sided-game formats can actually offer different physical stimuli and second, if the intensity (per unit of time) reported for the external load metrics recorded were adequate to stimulate players compared to the intensity reported during matches.

Methods

Participants

Twenty-four male professional soccer players of the same club were enrolled in this study (age = 27 ± 9 years old and body mass = 79 ± 15 kg). The inclusion criteria were the absence of illness and injuries and regular participation in soccer competition. Goalkeepers (GKs) were excluded in this study and only outfield players match data were evaluated. The sample size power was evaluated using G*power (Düsseldorf, Germany) for an ANOVA fixed effects, one way and results indicated that a total of 119 individual data points would be required to detect a *moderate* effect ($f = 0.35$) with 80% power and an alpha of 5%. The actual sample size of this study was of 279 individual data points, with a real power of >95%, which reduced the likelihood of type 2 error (false negative) (20).

External training load data was recorded as part of the normal monitoring routine of the club and was analyzed *a posteriori*. The Ethics Committee of the University of Suffolk (Ipswich, UK) approved this study (project code: RETHS22/016). Informed consent to take part in this research was signed by the club. All procedures were conducted according to the Declaration of Helsinki for human studies.

Experimental design

Drills were categorized as A) Large-sided games (LSG) 10vs10 (84 × 60 m), B) LSG 10vs10 (72 × 60 m), C) Hexagon possession 9vs9 + 3 (36 × 48 m), D) Possession gate 8vs8 + 2 (36 × 44 m), E) Possession 7vs7 + 3 (30 × 32 m), F) Small-sided games (SSG) 6vs6 (48 × 42 m), G) Possession 6vs4 (30 × 60 m). Only players that played for the full duration of the drill were included in this analysis. A total of 7 drills and 279 individual data points were included in this analysis. Offside rule was present during LSG formats only. No restriction on player's ball touches was applied for any sided-game drills. Additional balls were available around the pitches and were used to replace a ball that went out of the pitch—this was to allow the maintenance of intensity.

Sided-game drills description

LSG 10vs10 (84 × 60 m) and B) LSG 10vs10 (72 × 60 m) are sided-games that simulate a soccer match (with the same rules), involving regular goals and GKs, but in restricted space compared to a regular match, 229 m^2 and 196.4 m^2, respectively. The duration of these drills ranged from 7 to 10 min. Hexagon possession 9vs9 + 3 (36 × 48 m) is a possession drill with 3 neutral players free to move within a hexagon shaped pitch. The aim of the drill is to maintain possession of the ball for as long as possible and score "goals" by completing 6 passes. The opposition team are instructed to win the ball and instantly switch focus to maintain possession and score "goals" by completing 6 passes. The relative space size of the drill was 82 m^2. The duration of this drill was 8 min.

Possession gate 8vs8 + 2 (36 × 44 m) is a possession drill with 2 neutral players free to move on the pitch. The aim of the activity is to pass a ball through one of 3 gates (*i.e.*, small goals) where a teammate must receive the pass. The opposition team are instructed to win the ball and then instantly switch focus to scoring by passing the ball through one of 3 gates. The relative space size of the drill was 88 m^2. The duration of this drill was 7 min.

Possession 7vs7 + 3 (30 × 32 m) is a possession drill with 3 neutral players free to move within a rectangular shaped pitch. The aim of this drill is to maintain possession of the ball for as long as possible and score "goals" by completing 10 passes. The opposition team are instructed to win the ball and instantly switch focus to maintain possession for as long as possible. The relative space size of the drill was 56.5 m^2. The duration of this drill was 7 min.

SSG 6vs6 (48 × 42 m) are sided-games that involve regular goals and GKs, but in more restricted space compared to LSGs (*i.e.,*168 m^2). In this specific drill, the use of GKs and regular goals were used to maximize intensity. The duration of this drill ranged from 5 to 6 min.

Possession 6vs4 (30 × 60 m) is a possession drill with the aim of maintaining possession of the ball for as long as possible and scoring "goals" by completing 10 passes. The opposition team try to win the ball and then instantly switch focus to maintain possession for as long as possible. The relative space size of the drill was 180 m^2. The duration of this drill ranged from 5 to 6 min.

GNSS and data recording procedure

STATSports 10 Hz GNSS units (STATSports, Northern Ireland) with integrated 100 Hz triaxial accelerometer acquire and track multiple satellite systems (*i.e.*, global positioning systems, GLONASS) to provide highly accurate and reliable positional information (10). Apex units were validated for both linear and soccer-specific distances, reporting an error between 1 and 2.5% (10). The inter-units' reliability for sprints was previously reported and classified as *excellent* (intra-class correlation coefficient = 0.99), with a typical error of measurement of 1.85% for sprints ranging from 5 to 30 m (21).

Before each data recording, the GNSS Apex units were turned on about 15 min before the beginning. These units reported the quality of the signals that ranged between 17 and 21 satellites, which is in line with previous literature (21). All data recorded by the Apex units were downloaded and elaborated by STATSports software (Apex version Sonra v4.4.17) before being exported as a CSV. file for further analysis.

External and internal load variables

Distance covered, HSR distance (over 5.5 m·s^{-1} or 19.8 km·h^{-1}), and sprinting distance (over 7.0 m·s^{-1} or 25.2 km.h^{-1}) were analyzed in meters per minute (m·min^{-1}) (19). Total accelerations (>3 m·s^{-2}) and total decelerations (− < 3 m.s^{-2}) were analyzed as number of actions per minute (n.min^{-1}) (3, 15, 22). All external load metrics were reported as frequency per minute to decrease the difference of training (time) exposure. Players' internal load was quantified using their rate of perceived exertion (RPE) (Borg's CR10 scale) and expressed in arbitrary units (AU) (16). The construct validity of this scale was previously reported such as RPE was strongly correlated with heart rate ($r = 0.74$, $p < 0.001$) and blood lactate ($r = 0.83$, $p < 0.001$) during aerobic exercise (18).

Statistical analyses

Descriptive statistics are reported as mean ± standard deviation (SD). A Shapiro-Wilk test was used to check the assumption that the data conforms to a normal distribution. An analysis of variance (ANOVA) test was used to assess if significant differences exist between drills across several dependent variables. Effect sizes were reported using the eta squared (η^2) that express the amount of variance accounted for by one or more independent variables. η^2 was interpreted as >0.01 *small*, >0.06 *medium* and >0.14 *large* effect. If data were not normally distributed, a Kruskal-Wallis Test (non-parametric ANOVA) was performed. A homogeneity (equal variances across samples) test was performed using the Levene's test, and if a violation was found, the Brown-Forsythe correction was applied. When significant differences were found in the ANOVA, *post hoc* analysis was performed using Bonferroni corrections. Estimates of 95% confidence intervals (CIs) were calculated and reported in the figures. Effect sizes were interpreted using Cohen's *d* principle as follows *trivial* < 0.2, *small* 0.2–0.6, *moderate* 0.6–1.2, *large* 1.2–2.0, *very large* > 2.0 (23). Unless otherwise stated significance was set at $p < 0.05$ for all tests. Statistical analyses were performed in JASP (JASP Version 0.16.13. Amsterdam, Netherlands).

Results

Summary of the comparison between training load parameters during different drills is reported in **Table 1**.

The results of ANOVA for each external load variable are reported in the following figures: distance per minute in **Figure 1**, HSR per minute in **Figure 2**, sprinting distance per minute in **Figure 3**, accelerations per minute in **Figure 4**, decelerations per minute in **Figure 5**, RPE in **Figure 6**.

Post hoc analysis reporting delta difference, *p*-values with Bonferroni corrections and Cohen's *d* effect size for each drill and training load metric was reported in the **supplementary material**.

Discussion

The aim of this study was to quantify and compare the external and internal training load demands of sided-game drills in professional team players during the official season. In this study

TABLE 1 Comparison between training load parameters during different drills.

Variable	F-value	P-value	Effect size (η^2)	Qualitative interpretation
Distance per minute (m.min^{-1})	33.5	<0.001	0.426	Large
HSR per minute (m.min^{-1})	19.2	<0.001	0.298	Large
Sprinting per minute (m.min^{-1})	6.6	<0.001	0.127	Large
Accelerations per minute (n.min^{-1})	23.3	<0.001	0.340	Large
Decelerations per minute (n.min^{-1})	22.36	<0.001	0.331	Large
RPE (AU)	76.2	<0.001	0.628	Large

High-speed running (HSR), RPE = rating of perceived exertion. Eta squared (η^2) express the amount of variance accounted for by one or more independent variables. η^2 was interpreted as >0.01 *small*, >0.06 *medium* and >0.14 *large* effect. Unless otherwise stated significance was set at $p < 0.05$ for all tests.

we analyzed a variety of formats: LSG 10vs10, Hexagon possession 9vs9 + 3, Possession gate 8vs8 + 2, Possession 7vs7 + 3, SSG 6vs6, and Possession 6vs4. The first aim was to verify if different sided-game formats can offer different physical stimuli. We found that distance and HSR were greater in large-sided game (LSG) formats (LSG 10vs10) while acceleration and deceleration demands were greater in small-sided game (SSG) formats (SSG 6vs6 and Possession 6vs4). Interestingly, RPE was lower in the Possession gate 8vs8 + 2 format in comparison to all the other formats. These findings support the need for monitoring of training load during different sided-game formats implemented due to the large variation between drills in external and internal training load. The second aim of this study was to compare if the intensity of the external load metrics recorded were adequate to stimulate players compared to the intensity reported during matches. Although we found that sided-games can indeed replicate and occasionally exceed some intensity parameters, HSR and sprinting were consistently lower than what is found in official matches.

Distance per minute

Previous research reported that sided-game formats can be adapted to offer different physical demands (*i.e.*, distance per minute) (5, 24). LSG formats are usually used to obtain higher distance covered compared to SSGs or other formats (19). In this study, LSG 10vs10 (84 × 60 m and 72 × 60 m) was reported to have an average of 120.1 m.min^{-1} and 111.1 m.min^{-1}, respectively (**Figure 1**). In this case, a reduction in relative space size from 229 m^2 to 196.4 m^2 shows a significant ($p < 0.05$, d = 0.61, *moderate*) decrement in distance per minute. These values are supported by previous research that reported that sided-games ranged from 14.8 m·min^{-1} to 17.2 m·min^{-1} (8). Other formats such as Hexagon possession 9vs9 + 3 (duration = 8 min) and Possession gate 8vs8 + 2 (duration = 7 min) showed 96.8 m.min^{-1} and 101.7 m.min^{-1}, which were significantly lower ($p < 0.01$, *very large*) than LSG 10vs10 84 × 60 m (duration = 10 min). The relative space of the drill was 82 m^2 and 88 m^2, respectively. Therefore, it seems quite clear that a reduction in

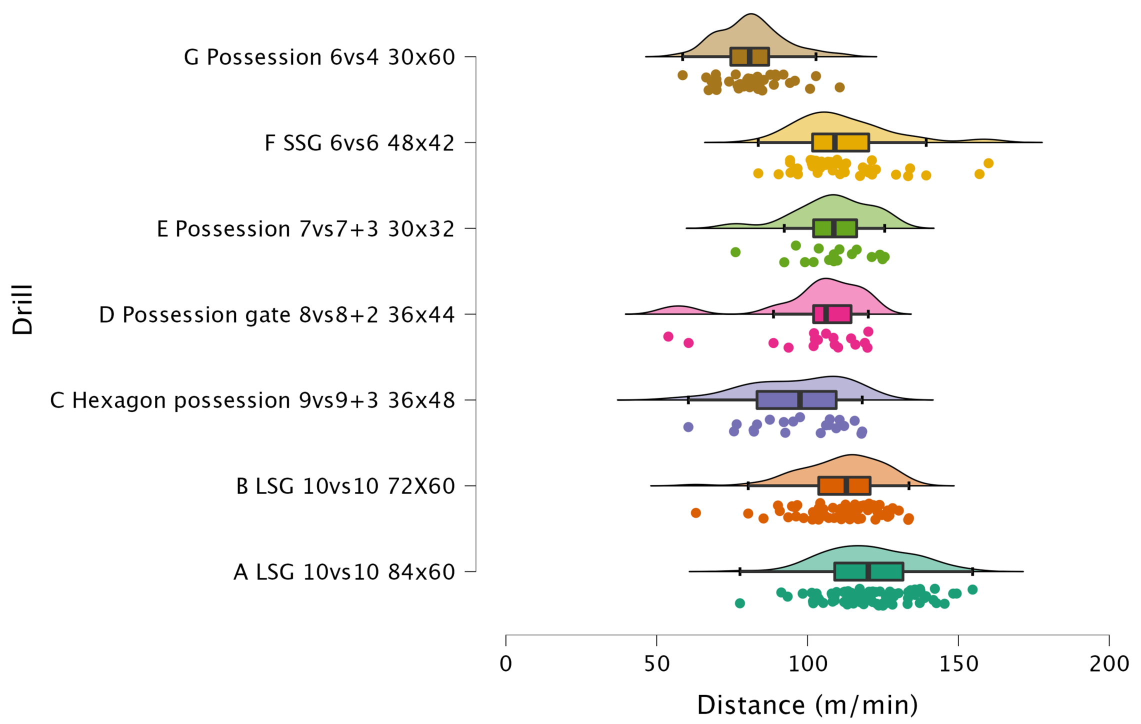

FIGURE 1
Comparison of distance per minute between drills. The data distributions show, mean, standard deviation, 95% confidence intervals, and individual data points.

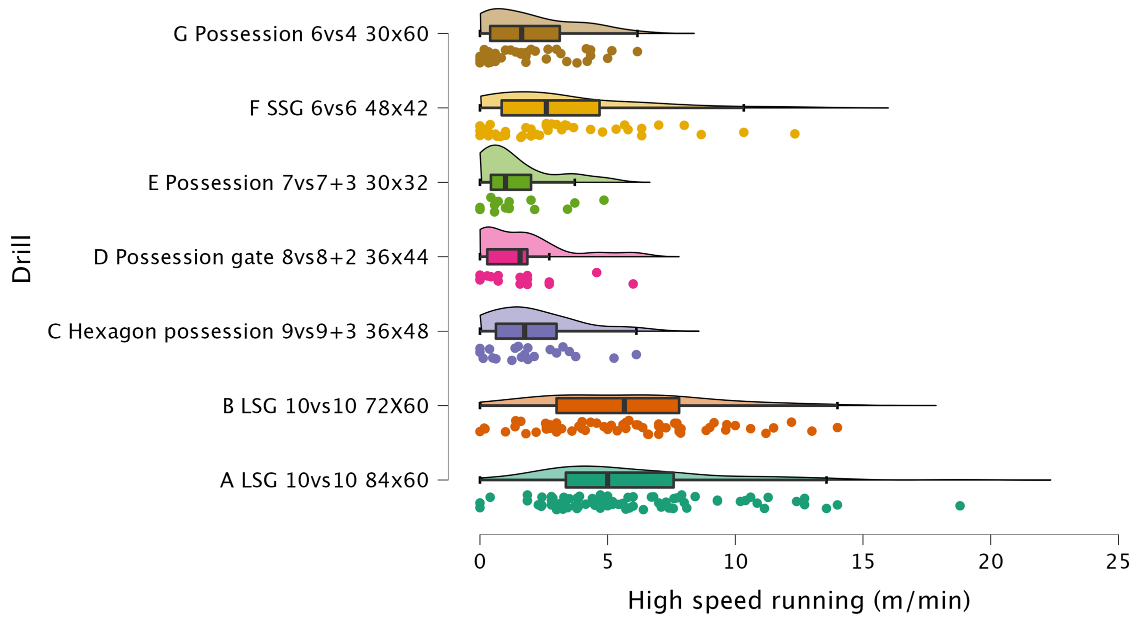

FIGURE 2
Comparison of HSR per minute between drills. The data distributions show, mean, standard deviation, 95% confidence intervals, and individual data points.

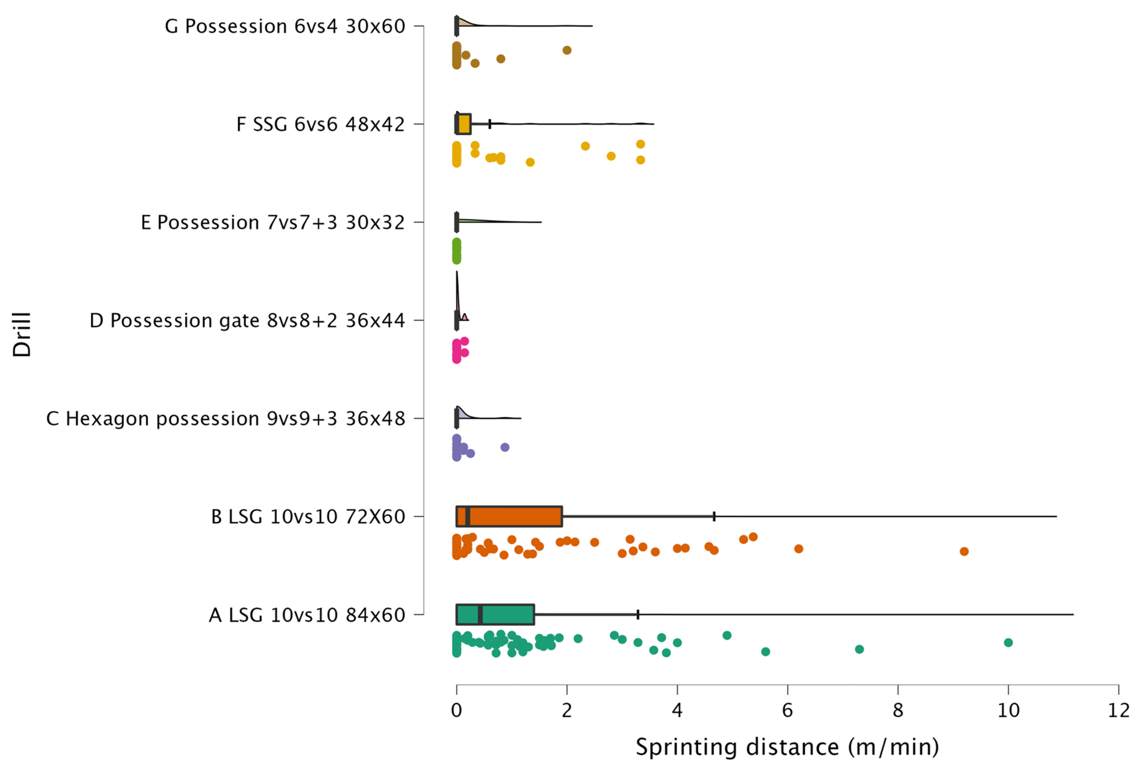

FIGURE 3
Comparison of sprinting distance per minute between drills. The data distributions show, mean, standard deviation, 95% confidence intervals, and individual data points.

relative space size reduces the distance per minute covered by players (25). A second factor that can affect distance per minute is the rules used during sided-games (7). For instance, Possession 6vs4 required players to play in an imbalanced way, specifically, the team with the ball would try to maintain its possession for as long as possible and "goals" were scored based on making 10

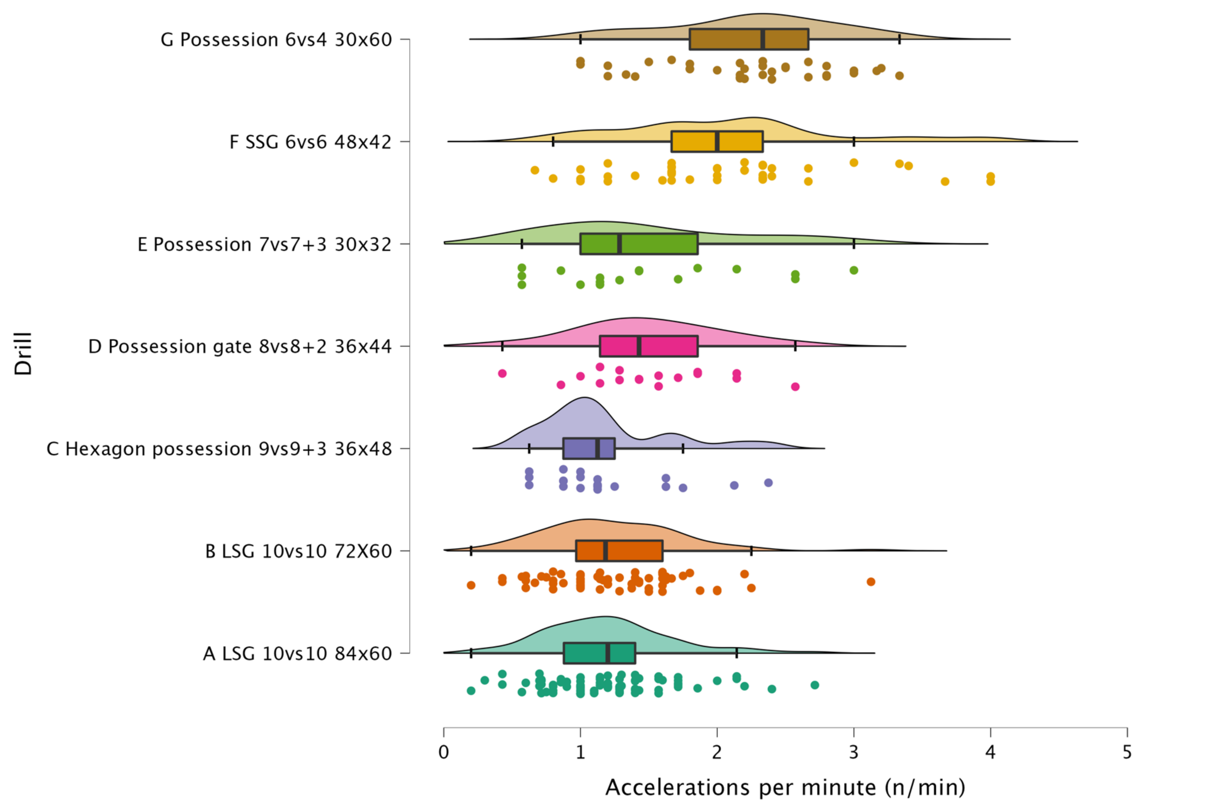

FIGURE 4
Comparison of accelerations per minute between drills. The data distributions show, mean, standard deviation, 95% confidence intervals, and individual data points.

passes. Although the relative space size was 180 m^2, the rules of the game did not enable the players to cover (81.3 $m.min^{-1}$) the same distance per minute of other possessions games. For example, possession 7vs7 + 3 (56.5 m^2) had an average of 108.3 $m·min^{-1}$ (d = 1.84, *large*). These results (see, **Figure 1**) show that a combination of appropriate relative space size and game rules are necessary to obtain the wished distance per minute output.

HSR and sprinting distance

In recent years, HSR and sprinting distance have been reported as among the most important external load variables for monitoring in soccer (3). Exposure to high-speed activities has a dual aim, first, to train the players for the demands of the match, second, to decrease the probability of lower limb non-contact muscular injuries (*i.e.*, hamstrings) (19, 26). In this study, we have observed that HSR and sprinting distance are greater in LSG compared to SSG (SSG = 168 m^2) and other possession formats played on a smaller relative space size (see **Figure 2** and **Figure 3**). LSG formats (229 m^2 and 196.4 m^2) enabled for greater HSR (5.9 and 5.6 $m.min^{-1}$, respectively) while 6vs6 SSG only enabled for 3.2 $m.min^{-1}$ of distance, which was significantly lower ($p < 0.01$, *moderate*). Significant differences were also found for sprinting distances, where players achieved 1.1 and 1.3 $m.min^{-1}$ in the LSG formats compared to a very low sprinting distance of 0.4 $m.min^{-1}$ during SSG formats. After a visual analysis of **Figure 2**, it is very clear that HSR is mainly achieved in LSG formats, while other formats such as SSG 6vs6 and Hexagon possession 9vs9 + 3 only offer lower exposures—most sided-game formats obtain trivial (<2 $m.min^{-1}$) exposures. A similar visual analysis of **Figure 3** shows very clearly that sprinting activity is mainly performed in LSG formats (although the actual distance per minute is minimal), while all the other sided-games show an average exposure lower than 1 $m·min^{-1}$. Therefore, a practical recommendation for practitioners is to use formats with a relative space size > 200 m^2 to generate HSR and sprinting distance with their players. The values found in this study are supported by a previous systematic review that found HSR ranged from 2.7 $m·min^{-1}$ to 3.6 $m·min^{-1}$ and sprinting distance ranged from 0.2 $m·min^{-1}$ to 0.7 $m·min^{-1}$ in a large sample ($n = 104$) of sided-games studies (8). It is clear from the previous research and from the results of this study that sided-games enable for a limited HSR exposure (apart from LSG, mean ranges = 5.9 and 5.6 $m.min^{-1}$) and very limited (if not trivial) sprinting distance exposure.

Accelerations, decelerations and RPE

Sided-games are frequently used in soccer to generate a mechanical load in the players' lower limbs. Although this mechanical load cannot be easily quantified (22, 27), sport scientists and coaches monitor the number of accelerations and decelerations performed during soccer-specific drills (15). In **Figure 3** and **Figure 4** is possible to observe that all formats

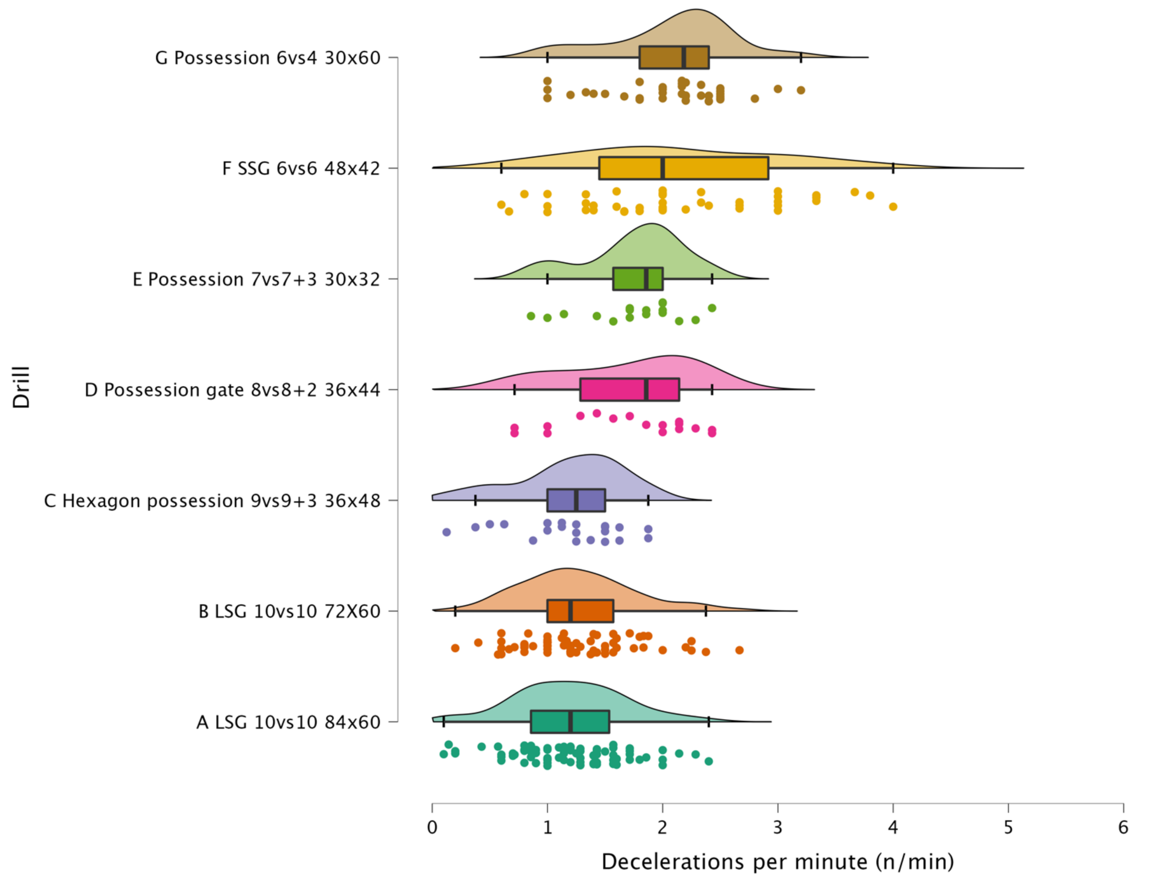

FIGURE 5
Comparison of decelerations per minute between drills. The data distributions show, mean, standard deviation, 95% confidence intervals, and individual data points.

used in this study can provide exposure to this type of actions that could be suitable to replicate the demands of the game and so to maintain/enhance physical performance. Of the sided-games monitored in this study, it is clear that Possession 6vs4 and SSG 6vs6 are more suitable than LSG formats for achieving accelerations and deceleration demands. The acceleration and deceleration demands of the possession 6vs4 and SSG 6v6 ranged between 2.1 and 2.2 $n.min^{-1}$, while only 1.2 accelerations or decelerations $n·min^{-1}$ were performed with LSG formats (**Figures 4** & **5**). The exposure to acceleration and deceleration efforts was significantly lower during LSG formats compared to Possession 6vs4 ($p < 0.01$, *moderate*). In addition to the use of external load parameters, practitioners can assess the players' internal load using an RPE scale, which is cheap and easy to implement (28, 29). RPE enables for a subjective quantification of the overall load that the players have perceived during the sided-games (7, 16). RPE correlates with internal load parameters (heart rate and blood lactate) (18) and has also been found to be sensitive to changes in acceleration intensity (22). In **Figure 6**, it is possible to evaluate the RPE of the sided-games assessed in this study; we can see that Possession gate 8vs8 + 2 shows the lowest score (RPE = 4.00 au) amongst all drills, while Possession 6vs4 and LSG 10vs10 (84 × 60 m) show the highest scores 8.0 and 7.5 au, respectively. The difference between Possession gate 8vs8 + 2 and the other two formats is *very large* and significant ($p < 0.01$), while the difference between the other drills ranges from *small* to *very large*. Although these results are of interest, partitioners need to be aware that RPE gives an indication of the overall perceived load, but it is not clear exactly what this score is composed of. Specifically, it is possible to see that Possession 6vs4 and LSG 10vs10 (84 × 60 m) have no significantly different scores ($p = 0.073$), but the formats characteristics and the external load parameters recorded are very different between these drills. Possession 6vs4 is played on a relative space size of 180 m^2, while a LSG 10vs10 (84 × 60 m) has relative space size of 229 m^2, the first is a possession game (with specific tactical aims), while the second is a goal-oriented format with different tactical aims. The HSR in Possession 6vs4 format is 1.9 $m.min^{-1}$ vs. 5.9 $m.min^{-1}$ of LSG 10vs10 (84 × 60 m), moreover, the number of accelerations were 2.2 per minute vs. 1.2 per minute. Therefore, professionals can use RPE to evaluate the overall perceived load of players during sided-games, however, some important considerations for its use and interpretation need to be made. The players' perceived exertion values can derive from different factors and cannot be easily interpreted when analyzed in isolation. For instance, sided-games with very different

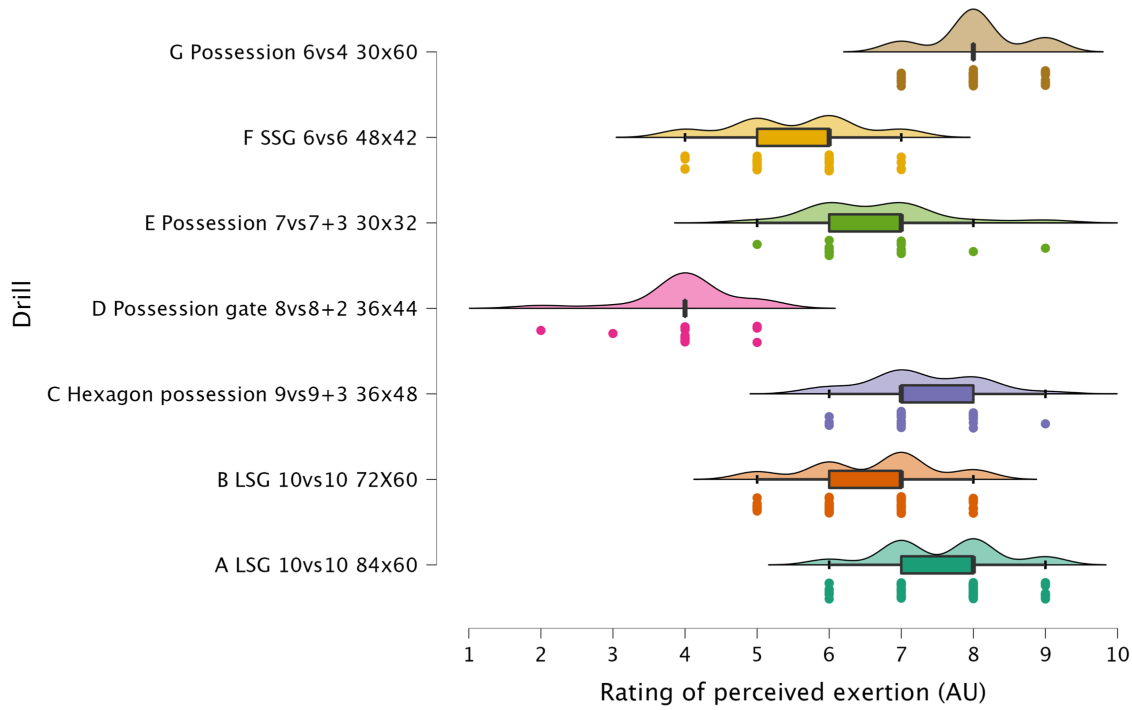

FIGURE 6
Comparison of RPE between drills. The data distributions show, mean, standard deviation, 95% confidence intervals, and individual data points.

characteristics and demands (accelerations or HSR) could give very similar RPE scores, however, the external load parameters and the tactical characteristics of the drills can be very different (and consequently, the real physical stimulus). Therefore, we suggest practitioners avoid focusing only on the use of RPE but to integrate external and internal load parameters in their monitoring system. These suggestions are supported by previous research that found very similar RPE scores during soccer-specific training protocols (30), although the accelerations and HSR demands of these formats were significantly different among them. The data reported in the literature (8, 12, 30), in addition to what found in the current research suggest the necessity for practitioners of assessing external load parameters in soccer to have a more complete understanding of players' training load.

Sided-games vs. matches

The sided-games monitored in this study should be compared with the intensity reported during official matches in order to understand if they can adequately train players for the intensity of the game. Previous research that analyzed players of a similar level (EFL League 1) reported that they covered a distance of 105.6 m.min^{-1} (31). The drills analyzed in this study had scores all above this intensity except for Hexagon possession 9vs9 + 3 (96.8 m.min^{-1}), Possession gate 8vs8 + 2 (101.7 m.min^{-1}), and Possession 6vs4 (81.3 m.min^{-1}). Therefore, if practitioners aim to replicate the distance per minute of official matches, they should select their drills accordingly (see **Figure 1**). However, practitioners should be aware that higher level football players (Dutch Eredivisie) reported higher distances 121.4 m·min^{-1} (32), therefore, the intensity found in this study should be reassessed when different players are used. Regarding HSR and sprinting distance, intensities of 7.0 m.min^{-1} and 1.5 m.min^{-1} were reported during official games, respectively (31). Observing the intensities indicated in **Figure 2** and **Figure 3**, it is possible to report that with the exception of the LSG formats, all the sided-games analyzed in this study offer an intensity that is much lower than what is reported during competitive matches (31). This is a critical point because sided-games are extremely popular training formats in soccer (7) but generally fail to fully prepare players for the high-speed demands of the game (8). Practitioners should therefore add other drills to their training routine (*i.e.,* ball-based circuit drills) (30) and linear sprinting exercises (without the ball) to prepare their players for competition (19, 33). Sided-games are also used to generate a mechanical load in soccer players, mainly because they offer exposure to acceleration and deceleration actions (15, 34). The physiological benefits of acceleration and deceleration activities (*i.e.*, short-shuttle runs) were well described in previous papers (35, 36). From a match perspective, players generally perform around 60–80 accelerations and decelerations per match (32, 37, 38), which mean around 0.6 and 0.9 actions per minute. **Figure 3** and **Figure 4** highlight that acceleration and deceleration demands during sided-games ranged from 1.2 to 2.2 and 1.2 to 2.1 n.min^{-1}, respectively. Our findings confirm that these drills can offer an adequate mechanical stimulus to prepare players for match demands. Practitioners can therefore use and manipulate the drill formats in the current study to generate the adequate mechanical load for their players as reported in the literature (15).

Limitations and future directions

This study is not without limitations, first, the players monitored in this study are professional athletes playing in EFL League 1, therefore, the intensity found could be different if higher- or lower-level players would perform the same sided-games. Therefore, practitioners of different clubs should verify these intensities with their players if using the same drills suggested here. Secondly, this study enrolled a sample of male professional soccer players, therefore these data cannot be easily used on female soccer populations. Recent research reported that more information and in particular more original studies are needed to increase the knowledge about female soccer (39), specifically, the number of articles are not comparable to current research output levels in male football. Thirdly, this study used a specific GNSS technology to monitor the external training load of the drills (10). Each technology has different accuracy and in particular, for the accelerations and decelerations, differences in filtering and acquisition frequency can make it difficult to compare outcomes amongst studies (15, 40).

Conclusions

This study found that the external and internal training load demands vary among sided-game drills in professional team players. Sided-game formats should be selected based on the coaches' technical and tactical aims but also consider the physical outcomes that they want to obtain. Match intensities can be trained using LSG 10vs10, SSG 6vs6 and Possession 7vs7 + 3 formats for some performance parameters (*e.g.*, distance per minute, accelerations, decelerations). LSG 10vs10 are the most suitable formats to achieve HSR and sprinting distance objectives, although the intensities recorded are lower than what was observed during regular matches. Practitioners should therefore also use other training methods to compensate for the external load recorded during sided-games such as ball-based circuits and linear sprinting drills. The acceleration and deceleration load can be comfortably achieved with several sided-games and in particular with SSG 6vs6 and Possession 6vs4 formats which offer a higher frequency of acceleration and deceleration actions per minute. Finally, RPE can be used as a subjective measure of perceived load, but practitioners need to be aware that sided-games with very different characteristics and load demands (accelerations and HSR) could obtain very similar RPE scores. Therefore, we suggest practitioners avoid focusing only on the use of RPE but integrate external and internal load parameters comprehensively within their monitoring system.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The Ethics Committee of the University of Suffolk (Ipswich, United Kingdom) approved this study (project code : RETHS22/016). The ethics committee waived the requirement of written informed consent for participation.

Author contributions

MB performed the data analysis and the first draft of the paper. AC recorded the data and reviewed the manuscript. KDK reviewed the manuscript. All authors contributed to the article and approved the submitted version.

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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.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2023.1150461/full#supplementary-material.

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Language games and blurry terminology: Can clarity enhance athlete development?

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This perspective focuses on the need for researchers and practitioners to carefully consider the clarity and consistency of their language in the context of athlete development. Evidence supporting a lack of congruency in the way certain terms and expressions are defined, understood, and operationalized continues to accumulate, highlighting the importance of this area for sport stakeholders and the potential looming crises. In systems that regularly rely on precision and accuracy, it will be critical that all involved in the co-creation of knowledge generation and application carefully consider terms that may further complicate athlete development practices. We highlight some potentially blurry terms and draw attention to potential avenues for future research.

KEYWORDS
athlete development, measurement precision, athlete selection, talent identification, careful language use

Introduction

> "*…words are the tools with which we work… Everything depends on our understanding of them*" —US Supreme Court Justice, Felix Frankfurter

In 1958, German philosopher Ludwig Wittgenstein suggested that linguistic confusion (i.e., the misuse and misunderstanding of language) was the root of all philosophical problems. He (1) further noted that "language games" (i.e., the use of language and the actions into which it is woven) are an inevitable facet of human behaviour. Individual perceptions and interpretations of various terminology[1] also exist as language is so heavily intertwined with one's experiences, which are profoundly shaped by sociocultural backgrounds, geographic locations, and education, among other variables. This inconsistency can have wide-ranging implications on research conceptualisation, sample descriptions, measurement precision, and practical applications due to differences in how terminology is operationalized (2).

The field of athlete development, which pertains to the identification, development, and selection processes of sporting populations, is not immune to these language challenges. Various undefined or vaguely defined terminologies have been recognized for causing confusion and contradiction in both research and practice. These "blurry" (i.e., unclear or

[1]Terminology is used to capture words, phrases, concepts, and constructs.

poorly defined) words are believed to be one of the main limitations of research and knowledge translation (3). At a time of sport datafication, characterized by the increased recording, analyzing, and interpreting of sport information (4), this is perhaps surprising. While this datacentric view of sport can offer many potential benefits (e.g., the possibility of hyper-specific training and development plans for athletes (5, 6), enhanced engagement for fans (7), and improved tactical decisions for coaches (8, 9), a deep concern remains; namely that the critical language used by coaches, researchers, and other sport stakeholders is often vague, nebulous, and lacking appropriate nuance. In our own areas of research (spanning talent identification, athlete selection, athlete development), some of these blurry terms have recently been exposed, such as "talent" (10), "elite" (11), "coach's eye" (12), "sampling" (13), "early specialization" (14), "mental skills" (15) and "positive youth development" (16). This work suggests the field is becoming increasingly aware of how problematic these words are and illuminates how difficult it can be to refine, replace, and/or remove such terms. This difficulty may be related to the frequent (mis)use of the terms found in discourse (e.g., policy or guiding documents), and further shared colloquially (e.g., in certain communities and groups) and discussed through media outlets.

Striking a balance between vagueness and conceptual clarity

> *"Among other things, the message is that we need to command a clear view of the use of our concepts, [and] be aware of the danger (and potential) of words…"* (3) (*p.* 90)

In some disciplines of sport science, such as sport psychology and sport sociology, it may be unrealistic to expect the same level of specificity and exactness we see in other domains. This is most likely a result of how "open" a system becomes (i.e., chaotic and dynamic) when considering a person's "performance" which encapsulates the interaction of social, genetic, environmental, cultural, spiritual, and psychological components, compared to disciplines like physiology and biomechanics, which are considered more "closed" systems (i.e., often objectively informed). It is also likely that some degree of blurriness could be seen as advantageous for athlete selection and development reasons. Take for example a coach whose career hinges on the selection of a successful cohort of athletes. With more vague and blurry selection criteria, this may create more "degrees of freedom" for him/her/them to defend the selection decisions they make. This notion also speaks to the art and science of coaching—where both scientific rigor coupled with creative and dynamic liberties are believed to be critical for coaching excellence (17, 18). However, there is an increasing push to clearly define and defend selection criteria, at least in high performance settings (19).

With this in mind, it might be advantageous to strike a balance between accepting conceptual vagueness and delineating sharp boundaries to quantify certain terms or phenomena. Determining *which* terms require greater focus, delineation, and precision is difficult; however, it could be argued that any term involving measurement requires precision. For example, "talent" is a blurry term, and incredibly hard to define (see (10, 20, 21)), yet it is often at the root of decision-making in many sport systems (e.g., when a team conducts a formal "talent identification camp"). Researchers and practitioners would undoubtedly benefit from increased conceptual clarity in the hope of making more accurate talent measurements and selections.

Perhaps it would be beneficial to even consider some terms on a scale or continuum instead of being binary and absolute (22). It is human nature to think of concepts and constructs in this rigid way (23), but sport rarely operates in such a fashion. In this sense, there could be value for terms that cannot be defined in a simple dichotomy to be considered relative to a scale or spectrum (e.g., early specialization; see (14) for a review). This type of theoretical and philosophical trade-off has been proposed in other fields, such as ecology, ecological economics, and computing (see (24–29) for examples), and while it is beyond the scope of this article to adequately present, let alone resolve, the disputes between philosophy and cognitive science, an emphasis should be placed on moving away from such blurry terms in the pursuit of making higher-quality decisions for athlete selection.

It is also important to acknowledge that organizational alignment, may be more critical than universal agreement. For example, player scouts (i.e., sport staff who assess athletes for their suitability for a given team) should have alignment in how they define certain aspects of sport (30). If two scouts hold substantially different definitions of "grit", then depending on which scout performs an assessment on an athlete, it will impact the way the scout reports and shares that information with others, thus impacting the way others perceive that athlete's grit. The organization could thus benefit from creating criteria or scales for what "grit" is and how it is portrayed by athletes, so there is greater organizational alignment. In other words, concepts do not always need to be rigidly defined, but the goal should be to improve the precision of measurement as much as possible over time as concepts become clearer. This will help stakeholders and organisations move collectively in the same direction (see **Figure 1**). For example, a recent scoping review on the conceptualization and measurement of positive youth development in sport revealed 243 unique operational definitions (16). This is clearly problematic, and since researchers and practitioners have different views of what the term and definition mean and how it is operationalised in research and practice, creating alignment is necessary to avoid such confusion and contradiction.

Improving conceptual clarity?

The reality is, language affects all stakeholders—the person who uses the language, the sport system he/she/they operates within, the athletes hearing the language, along with parents, other colleagues, and the list goes on. What we have learned from work conducted in the fields of psychology, language, and education (see (32) for an example), is that language can shape perceptions (i.e., belief about one's abilities and capabilities), goals (i.e., the type and nature of what is being strived for), and actions (i.e., the accompanied behaviours). For instance, beliefs about talent have

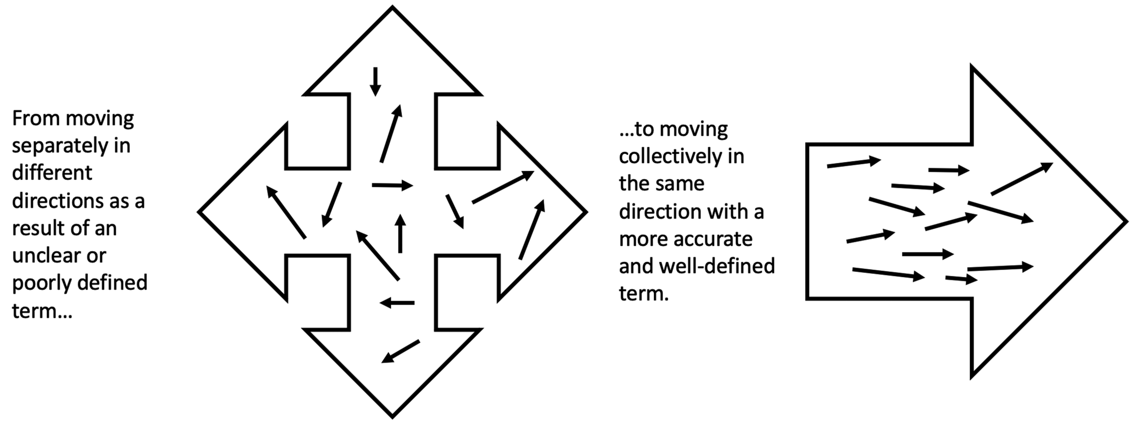

FIGURE 1
A visual depiction of how individual perceptions of terms may result in movement in various directions, but alignment can lead to a unified movement forward (adapted from (31)).

the potential to promote feelings of learned helplessness in contexts where athletes believe a lack of talent is insurmountable for their long-term aspirations (i.e., Pygmalion effects) or complacency in contexts where athletes believe their talent assures them future success and subsequently decreases their effort and motivation to improve (i.e., Crown Prince Effects (33). For this reason, it is important to carefully examine terms that could be considered blurry and, therefore, less useful than they might be appear.

Fortunately, determining a term's blurriness can be done through a process of identifying its definition within the contexts/situations that it is used. Take, for example, administrative staff in a sport organization trying to assess the quality of their talent selection criteria. The staff could attempt to define what "talent" means in the context of the sport, age, and level of athlete as well as within the environmental constraints of the sport system. If consensus, or even alignment cannot be reached on a definition (which seems likely given recent research (17)), this warrants a discussion on the value of "talent" in the system. This alignment is particularly important in an organizational setting, as it has been proposed that organizational alignment (in terms of values, priorities, and goals) may not just be important, but critical for success (34–36). In short, if a term cannot be defined, then how can it be measured, if it cannot be measured, how can it be monitored and improved, if it cannot be monitored and improved, what is its value? Below, we draw attention to three common terms used in athlete development research and practice as examples to help highlight the importance of clarity for stakeholders.

Elite. Telling athletes they are "elite" could have important effects on feelings of competence and motivation (37). In this sense, athletes may believe they have reached a certain status that may affect their thoughts about the value of training, how they compare themselves to others and other groups (i.e., on the competition hierarchy), and their ability to access important developmental resources. For instance, during the COVID-19 pandemic, lockdown restrictions were put in place in many countries with titles and labels used to restrict access to key developmental resources. However, due to the Olympic Games in Tokyo, competing athletes considered "elite" were allowed to continue training, without the limitations imposed on "non-elite" athletes. Determining what "elite" meant in this context caused considerable confusion and upset for many athletes. In the United Kingdom, "elite" was seen as broadly applying only to athletes 16 years of age and older, although this varied by sport (Category 1 and 2 youth soccer academies were allowed to continue across all ages) and by gender (no female academies were allowed to continue). It is perhaps unsurprising, that decisions at the policy level around what quantifies "elite" athletes have ripple effects into other aspects of sport. For example, labelling athletes as "elite" in sports science research considers them in a rather homogenous way. This can be misleading for a reader as important accompanying and qualifying information like age, playing level, sociocultural context, may not be included. This leads to further misinterpretations during research syntheses, where athletes may be grouped by their status (i.e., as "elite") despite being in vastly different contexts.

Character. The term "character" has been used as a selection criterion in sport for many years (38). In this context, coaches and selectors look to match an athlete's character traits to the priorities and values of the sport program/system. The term can become particularly blurry when examining the behaviours and mannerisms valued across different countries and sociocultural backgrounds. As an example, cultures that are considered to be individualistic (i.e., where the need of the individual supersedes the need of the group (39)) see behaviours such as asking questions, making eye contact, and challenging concepts to develop understanding as positive. In comparison, within collectivist cultures (i.e., where the needs of the group supersede the need of the individual (39), these same behaviours could be viewed as disrespectful (40). Based on these contexts, and depending on the cultural norms of the coach or selector (i.e., individualistic vs. collectivist), different aspects of a player's "character" could be assessed as either a positive or negative

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attribute. In a time when sport is working to reduce individual and systemic biases and inequalities (41–44), conceptual clarity may help achieve more equitable organisational structures by being clearer on what terms such as "character" entails.

Training load. The term "training load" term is generally used in reference to the physiological demand placed on an athlete, typically measured in terms of time (e.g., number of practice hours), energy expenditure (number of kilocalories burned), and/or stress (e.g., heart rate) (see (45) for more information). While these variables are relatively straightforward to quantify, they are incomplete proxies for overall "training load". Rarely considered are the "external" (i.e., demands placed on the athlete beyond training/practice and competition), "internal" (i.e., self-imposed demands) loads, and social and psychological loads from within and beyond the training environment that are a direct result of sport participation and training. For example, collegiate level athletes have demands from both their sport and academic careers (46). Arguably, overall training load should consider their academic demands as they are inextricably paired (i.e., without being an academically-eligible student, collegiate-level athletes cannot compete). As Farrow and Robertson (47) noted, using a periodized approach (i.e., systematic variations) to physical training is important, but it must consider additional dimensions of the training demand (both internally and externally), which can be difficult to capture given the complex interaction of an athlete's biological response to training stimuli as well as his/her/their developmental status. It is thus important to consider the context and the value of using a term like "load" more broadly, as it might be perceived as being reductionist and perhaps even disconnected from other critical psycho-social components of the athlete training experiences.

Moving forward

Athlete development appears to be at a watershed moment, with considerable research energy being spent on clarifying terms and improving measurement precision. Greater clarity in language will have impacts throughout the sport system, from researchers and policy makers to coaches at the frontlines of sport delivery. To help minimize these linguistic challenges, it could be valuable for the field to have a glossary/dictionary of frequently used words where some form of a consensus has been reached. The glossary/dictionary could benefit stakeholders by offering trustworthy, current, and peer reviewed definitions of terms that have been validated (i.e., tested/applied reliably across time and various diverse settings) and accepted (i.e., through a peer-reviewed system, the term was deemed "acceptable" for use) by multiple stakeholders in the field. As with the case of a language dictionary (e.g., the Oxford English Dictionary), the goal would be to create a "go-to" list of terms so that researchers and practitioners could utilize and reference such terms for consistency and clarity.

That said, approaches to create such a tool would undoubtedly come with challenges and obstacles. For example, decisions on "*who*" could/would contribute to such a tool would come with biases. Moreover, decisions on "*what*" definition(s) are included would likely be biased as well. To help reduce the impact of the "*who*" bias, ultimately, multiple stakeholders (e.g., researchers and practitioners) from different perspectives (i.e., spanning sport disciplines, countries, philosophical positions, cultures, competitive levels etc.) would contribute to create the *most appropriate* definition for that *point in time* based on the *current state of knowledge*. One approach could include using a consensus statement. The most popular of the consensus statement approaches includes the Delphi and "modified Delphi" designs (48), where groups of experts are asked their opinions on a particular issue/phenomenon (49) (see (50) for this approach applied in the context of sport). While these can be powerful tools for informing sporting policy and practice, there are important considerations. As noted by Blazey and colleagues (48), it is important for such consensus statements to carefully consider *who* might be missed in the consensus process, *who* may be coerced to agree on terms, and *how* can such statements capture the rich discussion that is had before the consensus has been reached. The authors also note that in many consensus statements, there is inadequate reporting of methods to allow for knowledge synthesis, drawing into question the rigor in the consensus process. To help combat this, Blazey and colleagues recommend a) reporting the criteria for the selection of "experts", b) reporting the selected panel's participant details (including their expertise on the topic in question), c) defining "a priori" what level of agreement is allowed and whether discordance will be reported, d) acknowledging opposing opinions, and e) externally validating results.

To help minimize the "*what"* bias, an emphasis should be placed on this being a "living document"– requiring updating as new evidence emerges, and relying on crowd sourcing to capture as many perspectives as possible. In this case, there would be not one, but multiple definitions that consider various philosophical perspectives on the meaning of language within different contexts (e.g., Wittgenstenian (1), Kuhnian (51), Popperian (52)) for researchers and practitioners to consider and reference. An alternative method to the consensus statement may include a text-mining analysis or possibly a survey of researchers and practitioners to identify what topics and terminology are the "blurriest". This could lead to a citation network analysis, which would be a useful step to establish the most impactful/cited authors and articles on a specific topic or terminology to determine what may be the most influential interpretations.

Final remarks

In this perspective, we acknowledged frequent use of "blurry" terms may be limiting the quality of evidence due to measurement imprecision. Amongst a growing field of research and practice in athlete development, it will be paramount for the sake of all stakeholders to remain attentive to the language they use. We believe the field is at a critical juncture where striking a balance between vagueness and conceptual clarity will be a necessity to advance the field forward in the right direction.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

All authors contributed equally to the conception, writing and editing of this paper. All authors contributed to the article and approved the submitted version.

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.

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Excellence fulfilled? On the unique developmental needs of professional athletes

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While the term "athlete development" has been used to capture the changes (physical, psychological, etc.) that occur as an athlete moves from initial sport engagement to elite performance, much of the research in this area has focused on earlier stages of the pathway, with very little work examining the highest levels of sport. Considering a person's bio-psycho-social development continues through adulthood, the limited attention to development for athletes at higher competitive levels is perhaps surprising. In this short article, we highlight several notable discrepancies between different competitive levels (e.g., pre-professional sport and professional sport) in the way development is conceptualized, contextualized, and operationalized. We use available evidence to provide guidance for researchers and practitioners to encourage the delivery of structured developmental programming in professional sport systems to aid with the transitionary period between pre-elite and elite levels, and to help foster career longevity.

KEYWORDS

athlete development, player longevity, sport administration, career transitions, talent development, talent retention

Key points

- Little is known about how to support athlete development at the highest levels of sport participation
- As athletes continue to develop and evolve, structured developmental programming is necessary to support athlete transitions, career longevity, and the overall athlete experience

Introduction

The sudden retirement announcement of the highest ranked female tennis player in the Women's Tennis Association in 2022, Ash Barty, came as a shock to many. Questions such as "*what led to this decision?*" and "*how could this have been prevented?*", drew attention to the limits of our understanding regarding athlete wellbeing, along with support and development for athletes at the professional level. Just as there are unique elements that relate to the quality of the coaching and learning environments during early development (e.g., we do not train youth as if they are mini adults), there are almost certainly factors related to later phases of development that underpin an athlete's capacity to thrive (i.e., balancing one's psychological, interpersonal, and physical resources) during this time. In this short piece, we argue that research initiatives and structured programming for athlete development are needed at the professional sport level, arguably with the same rigor and importance as pre-professional sport. Identifying and optimizing these factors could have important implications for wellbeing and performance at this level of athlete development – which may ultimately prevent unfortunate events such as the one had by Ash Barty.

It is important to note that the term "development" has multiple definitions, varying in context and priorities, but generally it relates to the process of growth, change, and stabilization across the lifespan. In the context of education, development is closely tied with learning. Although there is much discussion amongst scholars in the field of education about whether the environment should be formally (i.e., organized and structured) or informally (i.e., more happenstance) designed to maximize learning, nearly all models of learning and development propose a crucial role for the environment in influencing the type and quality of development that occurs. While there is value in exploring the impact of each of these components of the learning environment as it relates to sport, in this paper, we focus on "organized interventions" (1) and "deliberate programming" (2); that is, the formal and explicit environments that are designed to improve an athlete's development in some sense (e.g., physically, physiologically, emotionally, and/or psychologically).

This paper's authorship includes researchers and practitioners in various disciplines of sport science and professional practice, who together have recognized a deficit in peer reviewed research, coupled with a lackluster delivery of athlete developmental programs/initiatives with professional teams. To be fair, some teams do this better than others, but, as a whole, these initiatives are applied inconsistently at this level for a multitude of reasons (i.e., financial resources, interest, time, etc.). This paper draws together our perspectives on the matter framed against current evidence, to provide suggestions for researchers and practitioners on "*why*" and "*how*" to enhance the delivery of such programs. While we generally focus on North American professional sports (primarily the National Basketball Association, National Hockey League and Major League Baseball), many of the issues apply more generally in sport systems from other parts of the world.

Development in the context of professional sport

For athletes who make it to the professional level, most (if not all) have spent considerable time (i.e., years or even decades) in high-performance (i.e., excellence-driven) development systems. Along this pre-professional journey, athletes are typically provided opportunities to focus on developing the wide range of technical, tactical, physical and mental/psychological skills needed for exceptional performance in their sport. This is often embedded into the fabric of the sport program, and formally and informally woven into training and practice sessions.

One notable difference, however, between the pre-professional system and the professional system relates to the discrepancies in how "development" is prioritized. At the professional level, it appears (at least on the surface), that the primary outcome of interest shifts away from "development" and towards "maximizing performance". This may involve, for example, fine tuning aspects of injury mitigation (e.g., the increased use of strength and conditioning or focused recovery/medical practices) or tactical improvement (e.g., learning or modifying game strategies). Of course, performance coaches may also aim to improve and develop performance-related skills (e.g., improving a free throw in basketball or a pitcher's throw in baseball), but it seems that athletes are seen as more "fully formed entities" at the professional level than they would at lower levels of skill. In many ways they are (e.g., they would be expected to have a solid grasp of most of the "fundamentals" of their sport); however, there may be critical areas of personal and professional development that are neglected in many professional sport environments in North America.

Unique demands at the professional level

As suggested above, there may be unique developmental demands related to the professional environment. For instance, professional sports often have condensed travel schedules (e.g., 41 regular-season away games in a span of 6 months in the NBA and NHL) compared to the schedule of the amateur athletes in the same sport (e.g., amateurs usually have greater instability in their schedules with fewer competitions). These travel demands may limit opportunities for continued skill development for athletes and coaches. For instance, a recent development in some professional teams is "micro-dosing sessions" for the purpose of motor skill development, to accommodate the infrequency of an athlete being at their home training facility. Furthermore, travel demands may also increase an athlete's physical and mental load (i.e., volume of demands) while compromising approaches to recovery and learning (e.g., increasing the frequency of disruptions in sleep patterns), not to mention how it may affect their social and personal life (interactions with family and friends, caretaking, etc.). Relatedly, competition schedules may affect the types of performance-related priorities athletes (and teams) focus on. For example, a heavier game and travel schedule may result in athletes losing weight during the season. As a result, the focus for athletes and their support teams (e.g., sport medicine team) becomes maintaining muscle mass and injury prevention. At lower levels of competition, when athletes are less physically mature, there may be a bigger emphasis on gaining muscle mass and developing in ways that increase the likelihood of future success.

Differences in psycho-social demands are also important to consider. At the professional level, there are unique pressures on athletes that may be less prevalent in pre-professional or amateur sport. One of which is monetary pressure. In this sense, young players entering professional leagues are incentivized to progress in such a way that guarantees them a roster spot on the first team where they can make ten times (or greater) what their salary would be if they play in the "minor leagues". This adds an extra layer of pressure that collegiate or Olympic athletes, for instance, do not experience to the same extent. Of course, at later stages of athlete development, all individuals still in the system may navigate the possibility of developing into professionals in order to gain financial rewards, but this pressure is maximized in professional sports. More specifically, players can lose their spot on their team's roster, and large proportions, if not all, of the associated monetary rewards, on any given day. Closely connected to this change in earning is the fiscal responsibility that comes along with it. Sadly, there are numerous stories of professional athletes who sign significant contracts only to eventually find themselves in large debts (3, 4).

Challenges with developmental programming at the professional level

While these developmental differences between the levels of sport make intuitive sense, the reality is, there is little empirical evidence exploring these observations. Despite the importance of, and need for, this work at the professional level, improving understanding in this area will be difficult - undoubtedly because this type of work requires high-quality, longitudinal approaches. This type of research is challenging to do at the professional level for several reasons including confusing/conflicting terminology, regular movement of players from one team (i.e., developmental environment) to another, the influence of acute and chronic injuries, as well as privacy and confidentiality concerns with player data at this level.

These challenges will be hard to overcome for several reasons. Methodologically, factors related to professional athlete development are difficult to measure in valid and reliable ways (at least at the time of this article). Moreover, gaining access to these populations is difficult. Often there are strict confidentiality regulations in place to avoid "secret sharing" and to maintain competitive advancements (i.e., training techniques, within team research advances). Another challenge that is unique to professional settings is the difficulty in measuring the development and growth of players in such a homogenous pool, as well as different types of proxies that could be used to indicate progress. For instance, at junior levels of competition, progress can be assessed using performance benchmarks or tracking players who separate themselves from their peers by making to the next level. However, at the highest level of competition, where improvements in various facets of performance are more incremental, tracking and quantifying such progress is more difficult. Moreover, at this stage of skill, regular assessments to evaluate athletes' potential for success at the "next level" are typically over, meaning regular performance tests that extend beyond "performance" (i.e., their actual performance in their sport measured by metrics on the ice, field, court, etc.) are limited. This leaves a gap in understanding how progression occurs at the highest levels.

Overcoming obstacles: A call to action

Despite the challenging work ahead, solutions and evidence-informed programming may be within reach with appropriate effort. However, our optimism is bolstered by several factors. First, the funding available in professional sport for maximizing player development is impressive and may be accessible if appropriate links can be made between improving player development (and presumably indicators of health, wellbeing, and skill acquisition) and indicators with the greatest relevance to the team (e.g., improvements in competitive performance and/or returns on investment by developing players who are "in house" more efficiently). Second, the rapid growth in support team members with "development" in their job title emphasizes the latent potential already in the system. What is needed, however, is greater clarity on the priorities of such "development", but also training and education for those in that role to support such practices. This could include continued education for staff members including internal and external courses and workshops, focused on delivering high quality and evidence-informed practices for athletes. Finally, the interaction between scientific researchers and professional teams has increased considerably in the last decade (e.g., researchers are sometimes embedded into the staffing model), and this can offer access to domain-specific expertise, at a time when research is becoming more sophisticated and difficult to translate into practice, all while promoting efficiency in time and learning resources. Collectively, these factors suggest the time is ripe for meaningful work in this area.

Based on the limited prior work in this area, we propose a crude pathway for considering how players might develop during their professional careers and what might influence this development (**Figure 1**). In this pathway, players move through career stages (from rookie season to eventual performance decline), with each stage differing relative to what is occurring in an athlete's development during this time. For instance, athletes entering the professional league may need assistance making the transition from college or high-school levels into the new environment (5, 6). Ultimately, players' experiences in the league have the potential to lead to one of three outcomes. The majority will leave the league within the first year, while the majority of those who stay in the league have typical careers generally lasting on average between 5.5 years (for National Football League players) and 8.2 years (for NBA players) (7). A very small minority will go on to have "eminent" careers, ending up in the Hall of Fame or winning Most Valuable Player awards (8). Understanding how to optimize players' movements through these stages of a professional career, as

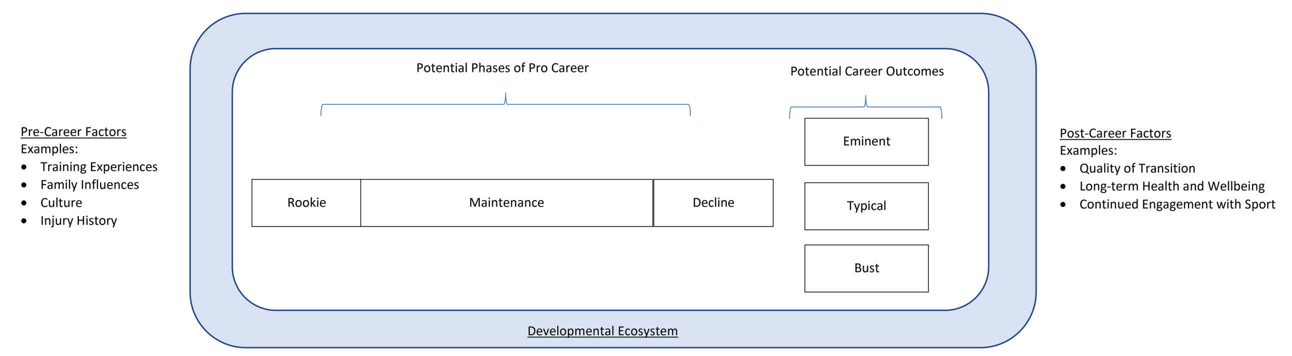

FIGURE 1
A proposed model of stages of a professional career. Each stage (i.e., initiation, maintenance, decline) will have specific goals and objectives that link to different performance and development outcomes. Furthermore, stages will be influenced by pre-career factors and the developmental ecosystem surrounding the athlete (e.g., organizational priorities, quality and nature of support system and resources, training and education available for those in developmental roles). Effective management of these objectives will influence post-career factors.

they relate to predicting these outcomes, remains an important area of future research.

Three areas of future research are suggested. The first is to explore *how* elements of development change across an athlete's professional career. Based on prior work on stages and phases of athlete development, it seems reasonable to assume there are qualitatively different "phases" across a professional athlete's career. These phases would be defined by changes in the weight/value of different developmental priorities. For instance, early in an athlete's time at the professional level it may be more critical to focus on helping them make the transition from "high potential amateur" to "proving your potential rookie". We know very little about the psychological dynamics occurring during the period, but it is likely they are highly nuanced and complicated. Moreover, we know little about how the environment of professional sport constrains this development (e.g., a rookie drafted to a stronger team may receive less playing time than one drafted to a weaker team, which may affect opportunities for development). After making this transition to the professional level, players may go through other phases as they attempt to maintain high levels of performance before the inevitable performance decline that leads to retirement and transition out of the professional system.

A second area to explore is the *types* of elements affecting player development outcomes at the professional level. Apart from a plethora of studies on the influence of various injuries (9, 10), few studies (7, 11) have examined predictors of career length. Even within these studies, the "success" of a professional athlete's career is captured using simple metrics (i.e., how long was their career?). Moreover, emerging concepts such as sporting "eminence" (8, 12) indicate that in addition to different phases across professional development, there are different outcomes for career achievement to be considered (e.g., was the athlete an "average" pro or an eminent one?).

Third, an obvious and important direction for future research is to examine the programmatic factors that predict these different metrics of career success. For instance, "player development" is perhaps the most rapidly growing category of personnel within professional sport systems. Understanding the relationships between different elements of the system, including the roles and responsibilities of different program staff, could provide insight that drives more efficient, cost-effective systems while improving player health, welfare, and performance. Moreover, understanding player needs across these crude stages (e.g., how they change over time and why) and exploring the importance of different categories of variables within each stage (e.g., performance-related changes vs. changes in social or psychological variables), may provide important indicators of player wellbeing.

Concluding thoughts

Research examining ways to promote and implement developmental programming for professional athletes remains scarce. What is clear, is that the ability to consistently demonstrate exceptional performance at this level reflects a complicated process of continued skill development, maintenance or improvements in strength and conditioning, and sustained general physical and mental health, usually alongside significant changes in life circumstances. For this reason, more work is needed to promote an increased understanding of ways to engage and support athletes across their entire sporting journey, along with ways to improve wellbeing, enhance sport experiences, and increase career longevity. In an era where professional athletes are known for their constant focus on performance in their sport, the news of Ash Barty highlights the complexity in balancing organizational success with an individual's expectations for success. In an effort to address the issues in the wake of Ash Barty's retirement and echoing her sentiments of, "I know how much work it takes to bring the best out of yourself. And…I don't have that in me anymore…"

re-thinking development is a critical endeavor for the future of professional sport (13).

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Author contributions

All authors contributed equally to the conception, writing, and editing of this paper. All authors contributed to the article and approved the submitted version.

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.

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Training load comparison between small, medium, and large-sided games in professional football

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This study aimed to assess if internal and external load parameters were different between sided game formats, if players' positions influenced these parameters, and if load parameters were different among sided game types (from 2vs2 to 10vs10) in professional football players. Twenty-five male players of the same club were enrolled in this study (age = 27 ± 9 years and body mass = 78 ± 14 kg). Sided games were categorized in formats as small-sided games (SSG, $n = 145$), medium-sided games (MSG, $n = 431$), and large-sided games (LSG, $n = 204$). Players were divided into roles such as center backs (CB), fullbacks (FB), center midfielders (CM), attacking midfielders (AM), and strikers (ST). STATSports 10 Hz GNSS Apex units were used to monitor external load parameters such as distance, high-speed running (HSR), sprinting distance, accelerations, and decelerations. The linear mixed model analysis found differences between formats ($p < 0.001$) for the rate of perceived exertion (RPE), distance, HSR, sprinting, accelerations, and decelerations. Differences were found between positions for HSR ($p = 0.004$), sprinting ($p = 0.006$), and decelerations ($p < 0.001$). Moreover, a significant difference was found between sided game types ($p < 0.001$) for RPE, distance, HSR, sprinting, accelerations, and decelerations. In conclusion, some sided games formats are more suitable for specific load-specific parameters (e.g., distance per minute, HSR, and sprinting are greater during LSG). The number of accelerations and decelerations is higher in MSG compared to other formats. Finally, players' positions influenced external load metrics, specifically HSR and decelerations but not RPE and distance.

KEYWORDS
soccer, team sports, performance, GPS, monitoring

Introduction

Football training aims to develop physical capacities, tactical and technical skills to compete during matches (1). In the latest years, sided games, which are categorized as small (SSG), medium (MSG), and large (LSG) formats, have been commonly used by coaches for simultaneously training these capacities and skills (2). Sided games are ball-based drills typically played on smaller pitch areas than regular games, with a fewer players and sometimes using modified rules to achieve specific physical, technical, and tactical aims (3, 4). From a conditioning perspective, sided games can improve aerobic and anaerobic fitness, acceleration and deceleration capacities (4, 5). Still, it has been reported that they may struggle to replicate the high-speed running (HSR) and sprinting demands of football matches (6, 7).

From a training management perspective, previous research found that sided games can be manipulated by changing the pitch sizes on which they are played to obtain a different relative area per player (3, 6). Indeed, HSR increases when larger relative pitch areas are used, while more accelerations and decelerations are performed when smaller relative pitch areas are used (7–10). During a microcycle (1 week) in football, specific sided games are selected and allocated to specific days (e.g., following the principles of tactical periodization) to achieve the desired physical stimuli to the players (11, 12). Sided games are commonly manipulated by changing the number of players involved in the sided games. For instance, SSG format includes 2vs2, 3vs3, and 4vs4, MSG format includes 5vs5, 6vs6, and 7vs7, and LSG formats included 8vs8, 9vs9, and 10vs10 sided games (7). Although a large body of research has investigated different aspects of sided games, we know that acceleration and deceleration demands as well as HSR and sprinting distances are highly variable among studies (7, 10). However, minimal information about thorough analysis from SSG (i.e., 2vs2) to LSG (i.e., 10vs10) within the same football team is available. This could be particularly interesting because it is known that the "one size fits all" approach to sided games actually does not work (13). Furthermore, it is known that players' positions play a role in the external load demands during matches (14). External positions usually require more HSR distance than center defenders or attackers, or in other cases, central positions require a greater number of accelerations and decelerations than external positions (14, 15). This could also be the case for external load demands during sided games, but it is unclear which games allow for different physical demands between positions. Coaches interested in manipulating training demands among positions during their training microcycle should understand these differences.

The quantification of training load is usually categorized into internal and external training load (16, 17). Internal training load is frequently assessed by collecting a player's rating of perceived exertion (RPE) (18, 19). RPE is cheap, easily administered and can capture a player's overall perceived load at the end of drills and sessions (20). Moreover, previous research reported that RPE score is correlated with other physiological measures such as heart rate and blood lactate (18). External training load is commonly monitored using the global navigation satellite system (GNSS) (2, 21, 22). GNSS has been proven to be valid and reliable to assess distance during linear and sport-specific tasks and determining peak speed (21, 23). Moreover, such technology can quantify the number of accelerations and decelerations during drills and sessions, which are critical parameters to consider during the weekly training plan in football (10). Because the difference in internal and external training load between sided games formats as well as the effect of players' positions on such parameters are not clear, a specific study investigating these variables is needed. Therefore, we aimed to verify if internal and external load parameters were different between sided-game formats (SSG, MSG, LSG) and if players' positions influenced these parameters. Finally, we intended to clarify whether internal and external load parameters differed among sided-game types (from 2vs2 to 10vs10) in professional male football players.

Methods

Participants

Twenty-five male professional football players of the same club were enrolled in this study (age = 27 ± 9 years and body mass = 78 ± 14 kg) during the 2022–23 season. The inclusion criteria included the absence of illness and injuries and regular football training and competition participation. Goalkeepers (GKs) were excluded from this study, and only outfield players' match data were evaluated. The sample size estimation was calculated using G*power (Düsseldorf, Germany) for a one-way ANOVA fixed effect that indicated a total of 159 individual data points would be required to detect a *small* effect ($f = 0.25$) with 80% power and an alpha of 5%. The actual sample size of this study was 780 individual data points, with a real power of >95%, which reduced the likelihood of type 2 errors (false negative) (24). The Ethics Committee of the University of Suffolk (Ipswich, UK) approved this study (project code: RETHS22/016). Informed consent to take part in this research was signed by the club. The external training load data was recorded as part of the regular monitoring routine of the club and was only analyzed *a posteriori*. All procedures were conducted according to the Declaration of Helsinki for human studies.

Experimental design

Sided games were categorized in formats such as SSG ($n = 145$), MSG ($n = 431$), and LSG ($n = 204$). SSG included 2vs2, 3vs3, and 4vs4 sided games; MSG included 5vs5, 6vs6, and 7vs7 sided games; LSG included 8vs8 and 10vs10 sided games (7). During these sided games goals were included as well as GKs, football balls around the pitch were available to be used when one ball was kicked off the pitch, and coaches encouraged players to increase intensity. Only players that completed the drill were included in this analysis. Players were divided into positions such as center backs (CB), fullbacks (FB), center midfielders (CM), attacking midfielders (AM), and strikers (ST). The specific number of data points per position is reported in the **Supplementary Material**.

Sided game type

(a) 2vs2 SSG played with the same rules of a match in restricted spaces, using a medium pitch format, with a relative pitch area of 121 m^2.
(b) 3vs3 SSG played using a small pitch format, with a relative pitch area of 72 m^2.
(c) 4vs4 SSG played using small and medium pitch formats, with a relative pitch area of 68 m^2 and 104 m^2, respectively.
(d) 5vs5 MSG played using small and medium pitch formats, with a relative pitch area of 72 m^2 and 115 m^2, respectively.

(e) 6vs6 MSG played using small and medium pitch formats, with a relative pitch area of 67 m^2 and 140 m^2, respectively.
(f) 7vs7 MSG played using medium pitch formats, with a relative pitch area of 102 m^2 and 144 m^2, respectively.
(g) 8vs8 LSG played using a medium pitch format, with a relative pitch area of 157.5 m^2.
(h) 10vs10 LSG played using large and regular pitch formats, with a relative pitch area of 229 m^2 and 353.4 m^2 (108 m × 72 m), respectively.

The specific number of data points per sided game type is reported in the **Supplementary Material**.

SSG, MSG, and LSG formats were arbitrarily categorized as small pitch size (<99 m^2), medium pitch size (from 100 to 199 m^2), large pitch size (from 200 to 289 m^2), and regular pitch size >290 m^2, which is the minimum standard size (100 m × 64 m) of a football pitch for a professional 11-a-side game set by Fédération Internationale de Football Association. In this article, the regular pitch size used was 108 m × 72 m, equivalent to 353.4 m^2 per player (including GKs).

Global navigation satellite system (GNSS)

In this study, STATSports 10 Hz GNSS Apex units (Northern Ireland, UK) were used to monitor SSG, MSG, and LSG. GNSS technology tracks multiple satellite systems (i.e., global positioning systems, GLONASS) to provide highly accurate and reliable positional information (21). Moreover, Apex units are integrated with a 100 Hz triaxial accelerometer (25). Before each training session (e.g., 15 min), the GNSS Apex units were turned on to allow the units to track an adequate number of satellites. These units reported the number of satellites tracked that ranged between 17 and 23, which is in line with previous literature (26). All data recorded by the Apex units were downloaded and elaborated by STATSports software (Apex version Sonra v4.4.17) before being exported as a CSV file for further analysis.

Previous research reported the validity and reliability of this technology during linear and soccer-specific tasks reporting an error of <2.5% (21). The reliability (inter-unit) during sprinting actions (range: 5–30 m) was *excellent* (intra-class correlation coefficient = 0.99), with a typical error of measurement of 1.85% (26).

External and internal load variables

Players' internal load was expressed in arbitrary units (AU) and monitored using a previously validated scale, specifically Borg's CR10. This scale assesses players' rate of perceived exertion (RPE) (18, 27). Each player gave their RPE score after the end of each sided game (28). External load metrics were quantified and reported as frequency per minute to account for the difference in time exposure. In this study, GNSS recorded metrics were

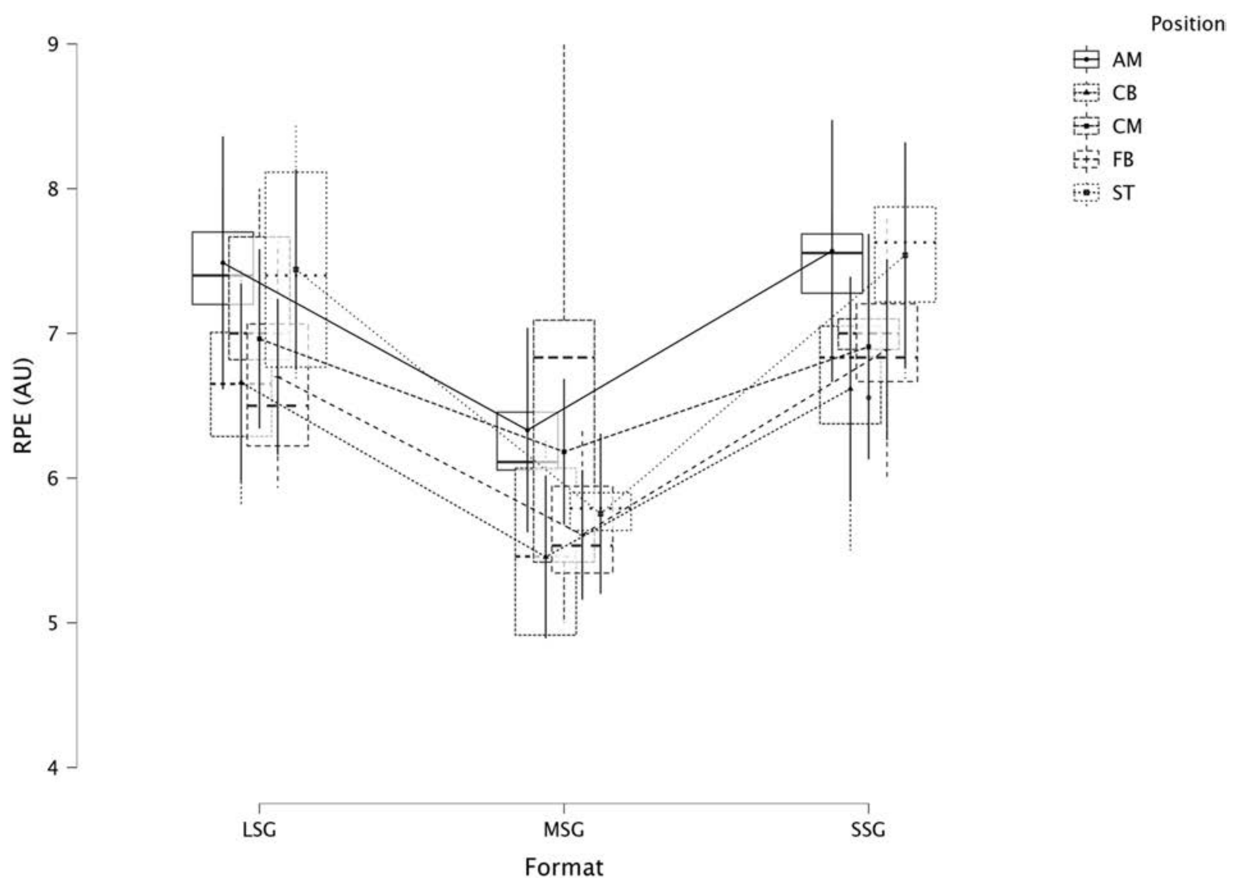

FIGURE 1
Comparison of RPE between formats and positions.

distance covered ($m \cdot min^{-1}$), HSR distance ($>19.8\ km \cdot h^{-1}$), and sprinting distance ($>25.2\ km \cdot h^{-1}$) (8). The number of high-intensity accelerations ($>3\ m \cdot s^{-2}$), and decelerations ($<-3\ m \cdot s^{-2}$) were quantified using GNSS technology (10).

Statistical analyses

Descriptive statistics are reported as mean ± standard deviation (SD). A Shapiro-Wilk test was used to check the assumption that the data conforms to a normal distribution and that the residuals were found normally distributed for the linear mixed model (LMM). The primary analysis was an LMM, which used the Satterthwaite method (degrees of freedom estimation based on analytical results) to assess if significant differences exist between formats (LSG, MSG and SSG; fixed effects) and players' positions (fixed effects) across several dependent variables (29). Players were considered as random effect grouping factors. During the secondary analysis, individual sided games (from 2vs2 to 10vs10, fixed effects) and players (random effects) were analyzed using again a LMM. When significant differences were found in the LMM model, an estimation of marginal means (contrasts) was performed using Holm's corrections for multiple comparisons. Estimates of 95% confidence intervals (CIs) were calculated and reported in the figures (Box Plots). Effect sizes were calculated from the *t* and *df* of the contrast and interpreted using Cohen's *d* principle as follows *trivial* < 0.2, *small* 0.2–0.6, *moderate* 0.6–1.2, *large* 1.2–2.0, *very large* > 2.0 (30). Unless otherwise stated significance was set at $p < 0.05$ for all tests. Statistical analyses were performed in JASP (JASP Version 0.16.13. Amsterdam, Netherlands).

Results

The summary of the comparison between formats (LSG, MSG, and SSG) and positions using a LMM across several dependent variables is reported in **Figure 1** (RPE), **Figure 2** (distance), **Figure 3** (HSR), **Figure 4** (sprinting), **Figure 5** (accelerations), **Figure 6** (decelerations).

LMM analysis for formats (LSG, MSG, and SSG) and positions reported a significant difference between formats ($F = 34.3$, $p < 0.001$) but not for positions ($p = 0.084$) for RPE. LMM analysis reported a significant difference between formats ($F = 167.3$, $p < 0.001$) but not for positions ($p = 0.119$) for distance. LMM analysis reported a significant difference between

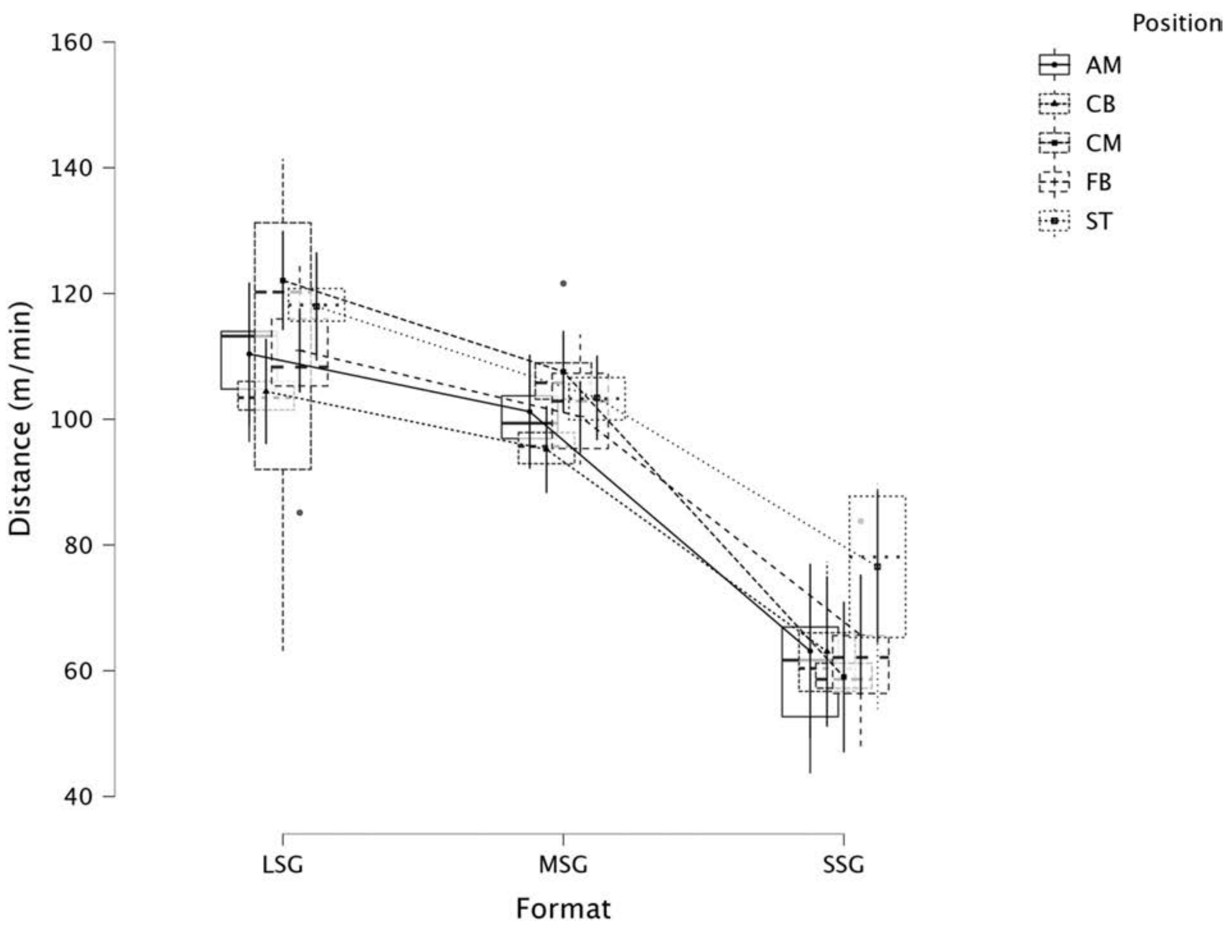

FIGURE 2
Comparison of distance between formats and positions.

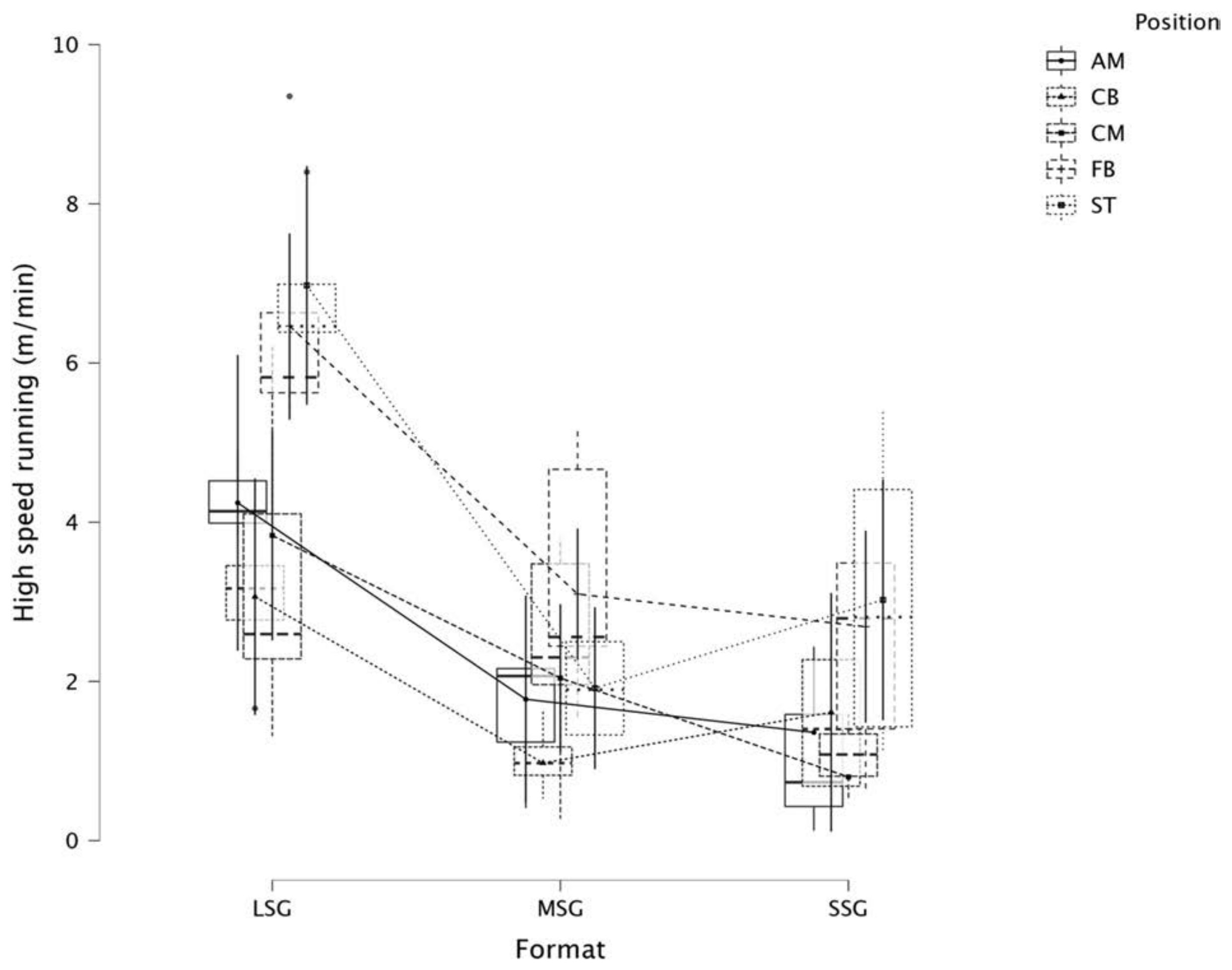

FIGURE 3
Comparison of HSR between formats and positions.

formats ($F = 66.1$, $p < 0.001$) and positions ($p = 0.004$) for HSR. LMM analysis reported a significant difference between formats ($F = 16.4$, $p < 0.001$) and positions ($p = 0.006$) for sprinting distance. LMM analysis reported a significant difference between formats ($F = 47.6$, $p < 0.001$) but not for positions ($p = 0.115$) for accelerations. LMM analysis reported a significant difference between formats ($F = 28.9$, $p < 0.001$) and for positions ($p < 0.001$) for decelerations.

Summary of the secondary analysis, where individual sided games (from 2vs2 to 10vs10) were analyzed as presented in **Figure 7** (RPE), **Figure 8** (distance), **Figure 9** (HSR), **Figure 10** (sprinting), **Figure 11** (accelerations), Figure **12** (decelerations). LMM analysis reported a significant difference between sided game types for RPE ($F = 28.1$, $p < 0.001$), distance ($F = 50.6$, $p < 0.001$), HSR ($F = 14.5$, $p < 0.001$), sprinting ($F = 4.38$, $p < 0.001$), accelerations ($F = 19.8$, $p < 0.001$), and decelerations ($F = 14.8$, $p < 0.001$).

The descriptive analysis of sided games formats (LSG, MSG, and SSG), players' positions (CB, FB, CM, AM, and ST), and sided game types (from 2vs2 to 10vs10) is reported in the **Supplementary Material**.

Estimated marginal means and 95% CIs for sided games formats (LSG, MSG, and SSG), players' positions (CB, FB, CM, AM, and ST), and sided game types (from 2vs2 to 10vs10) were reported in the **Supplementary Material**.

Discussion

This study aimed to verify, first, if internal and external load parameters were different between sided-game formats (SSG, MSG, LSG), second, if players' positions influenced these parameters, and finally, if internal and external load parameters were different among sided-game types (from 2vs2 to 10vs10) in professional male football players. We found that internal training load (RPE) changes among sided-game formats. For instance, MSG reported a lower score compared to LSG. External training load parameters are significantly different among formats where, for example, distance per minute is greater during LSG than SSG, and the number of accelerations was greater in MSG than LSG. Players' positions do not affect internal training load among the formats, while they influence some external load

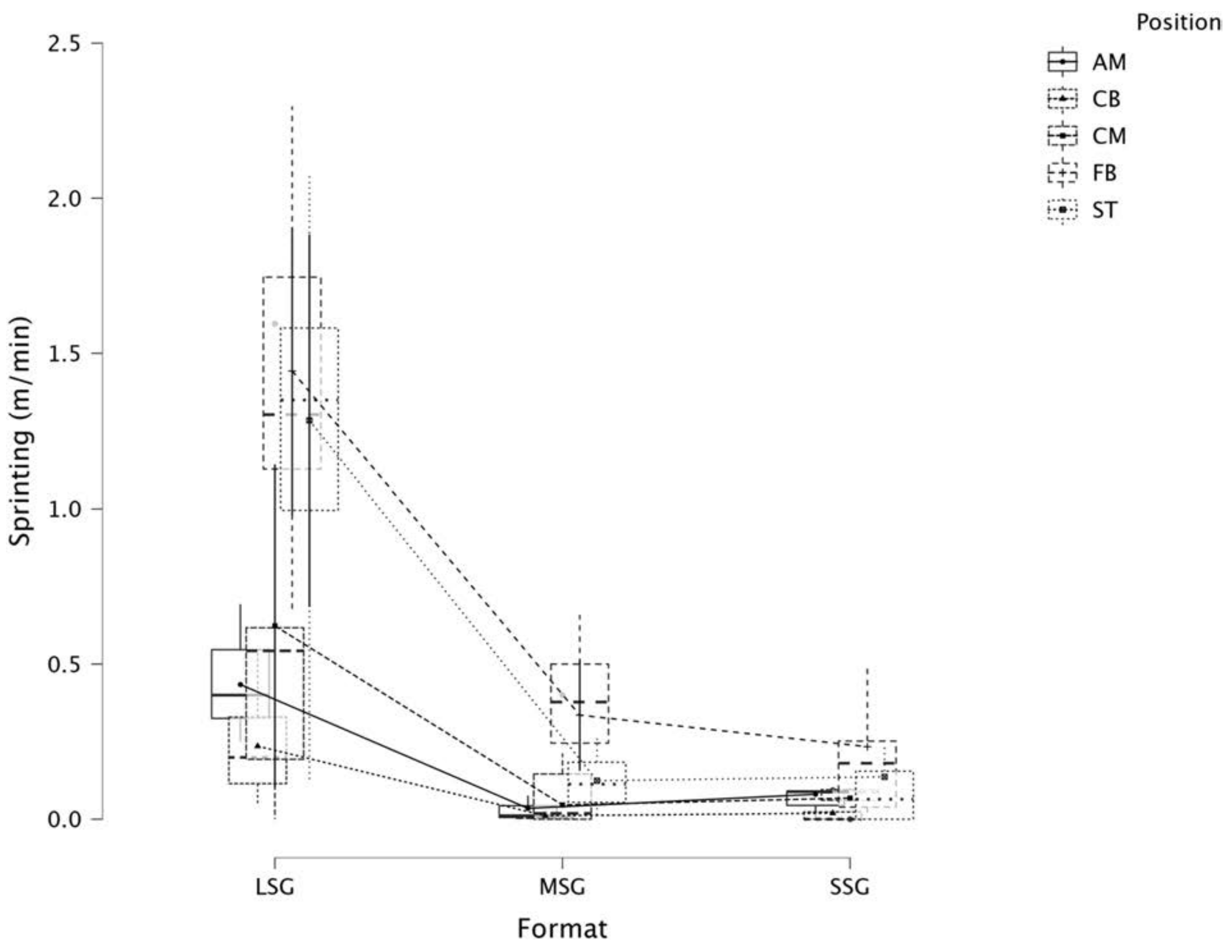

FIGURE 4
Comparison of sprinting between formats and positions.

parameters; for example, HSR and sprinting distance are greater for ST and FB compared to CB. Finally, both internal and external load parameters were found to be different among sided games (from 2vs2 to 10vs10), where LSG 8vs8 was found to be the most demanding drill for distance covered per minute, and LSG 10 vs. 10 was found to be the most demanding drill for HSR and sprinting. On the other hand, acceleration and deceleration demands were greater in MSG 5vs5 and MSG 6vs6 compared to other formats.

Internal and external load parameters between sided game formats

RPE was found to be significantly ($p < 0.001$) different between formats (**Figure 1**). Specifically, RPE in LSG was greater than RPE in MSG ($p < 0.001$, d = *very large*) while RPE in SSG was greater ($p < 0.001$, *very large*) than in MSG. From a practical perspective, practitioners can use RPE as a cheap monitoring tool for evaluating players' perceived load during sided games (18). However, when RPE is not associated with other external load data, interpreting why these differences between sided games formats exist is quite difficult. In this context, practitioners cannot understand if RPE differences among formats is due, for example, to a greater distance covered or because of a higher number of accelerations performed by the players. Therefore, we suggest practitioners use both internal and external load parameters to have a clearer picture of the demands of their sided game drills (31). Last but not least, RPE is not a pure measure of intensity because it is affected by the duration (of the drill), therefore, practitioners should be conscious of this when they compare drills of different duration. This study analyzed distance covered per minute, one of the most common parameters monitored in football (**Figure 2**). LSG formats obtained greater distance covered (*moderate* to *very large*) than the distance covered during MSG and SSG. While MSG ($101.3\ m\cdot min^{-1}$) reported a significantly greater distance compared to SSG ($65.6\ m\cdot min^{-1}$). Practitioners should preferentially use LSG and MSG when they want to replicate intensities (distance per minute) near match intensity, while SSG are clearly too small to allow for match-specific demands (7, 32). When HSR distance is analyzed, LSG reported a greater distance ($5.0\ m\cdot min^{-1}$, $p < 0.001$) compared to MSG ($2.1\ m\cdot min^{-1}$) and SSG ($2.0\ m\cdot min^{-1}$). This result is in line with previous research

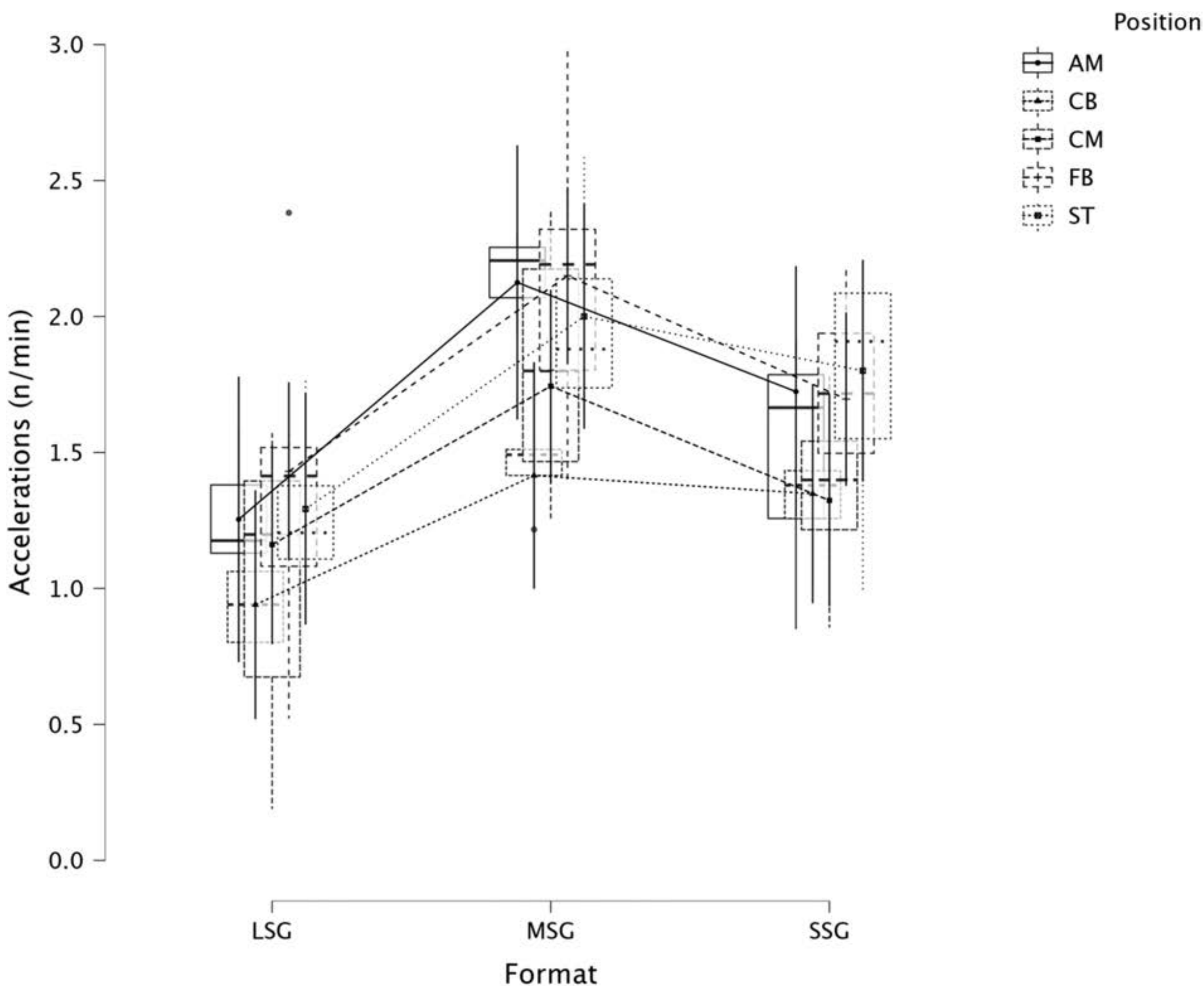

FIGURE 5
Comparison of accelerations between formats and positions.

that reported that HSR distance is greater in LSG compared to smaller formats (2, 7). Moreover, previous research reported that LSG are generally suitable to achieve sprinting speed, while smaller formats struggle to do so (8). This is supported by the data of this study, where sprinting distance is exclusively found in LSG (0.9 m·min^{-1}), while MSG and SSG reported distances close to zero (around 0.1 m·min^{-1}). These data confirm that, first, LSG using large spaces (>200 m^2 per player) or with regular dimensions (>290 m^2) are needed to achieve both HSR and sprinting distances, and second, that players very likely need to perform some running based exercises (e.g., linear sprinting activities) to actually cover an adequate amount of sprinting distance during their microcycle if SSG and MSG are mainly used (8, 33). Practitioners should also consider that matches or their "replication" using regular pitch areas (like in this study, 10vs10 = 353.4 m^2) in training can be a potent stimulus for physical development (17, 34). Sided games are also used to generate mechanical and physiological loads in the lower limbs (35, 36); since direct quantification is highly complicated in a football context, practitioners usually quantify accelerations and decelerations (10, 37) using GNSS technology (23, 38). This study found that the number of accelerations is greater in MSG compared to LSG (*large*) and SSG (*small*). It is shown that SSG is not the best format for loading (when accelerations are the reference) players, but MSG is. Very similar results were found when decelerations were analyzed; MSG reported a significant (p < 0.001) greater number of decelerations compared with both LSG (*large*) and SSG (*moderate*).

Players' positions and internal and external load parameters

In this study, we also analyzed players' positions' effect on internal and external load parameters. RPE and distance covered per minute were not significantly affected by positions, $p = 0.084$ and $p = 0.119$, respectively. Therefore, players of different positions can achieve a similar RPE or relative intensity during sided game formats. However, this was not the case when HSR distance was analyzed (**Figure 3**), specifically, CB (1.9 m·min^{-1}) reported a significantly lower value compared to FB (4.1 m·min^{-1}, $p = 0.006$) and ST (4.0 m·min^{-1}, $p = 0.014$), as well

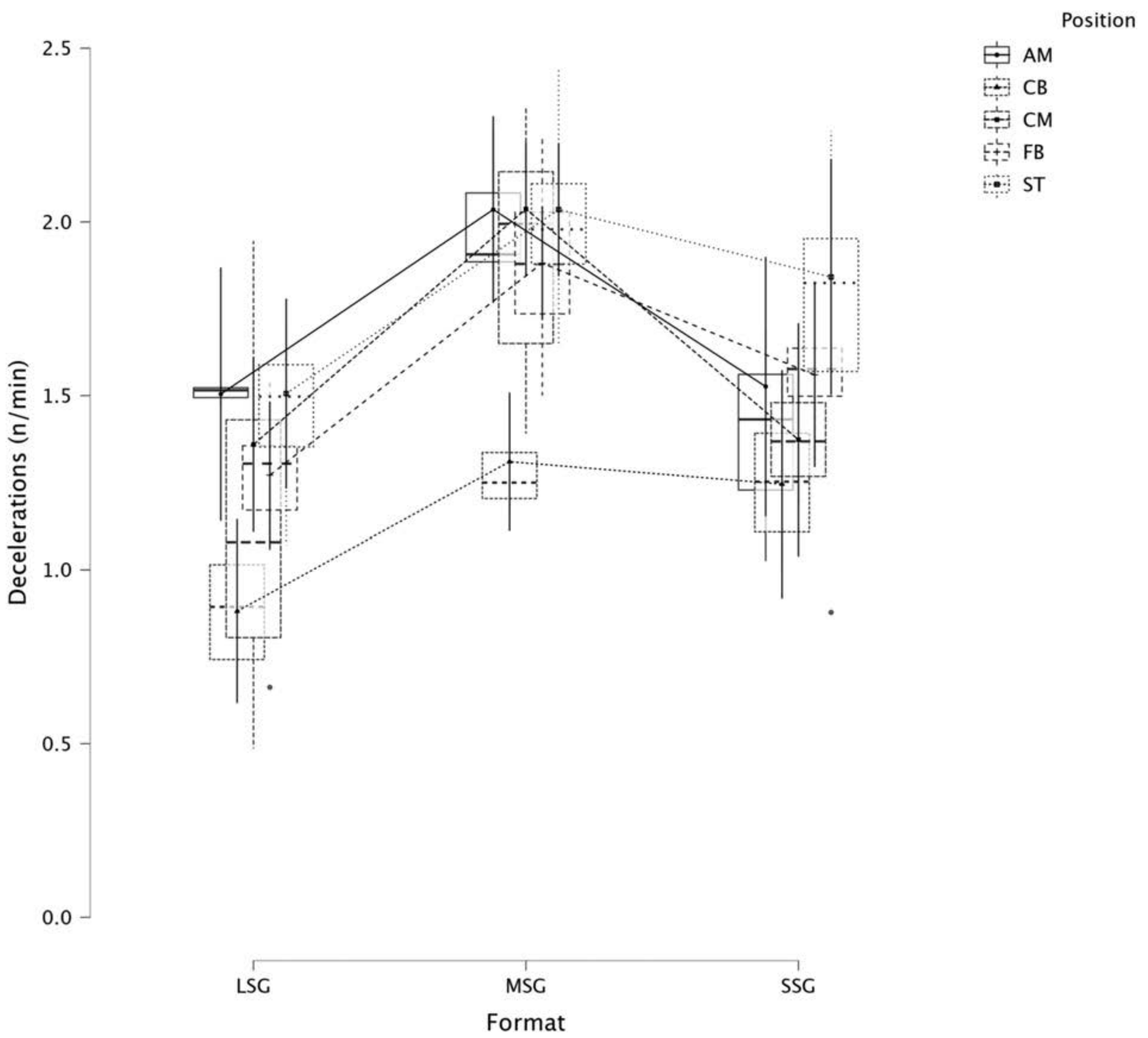

FIGURE 6
Comparison of decelerations between formats and positions.

as ST covered significantly more HSR than CM (2.2 m·min^{-1}, p = 0.016). This means that coaches can use sided games to stimulate players based on their position. When sprinting distance was analyzed we found a significant difference between positions ($p = 0.006$, Figure 4), specifically, FB (0.7 m·min^{-1}) outperformed the other positions such as AM ($p = 0.025$), CB ($p = 0.005$), and CM ($p = 0.025$) but they had a similar sprinting distance compared to ST (0.5 m·min^{-1}, $p = 0.329$). These results highlight that while positions do not affect RPE scores or the distance per minute, they affect HSR and sprinting distance, therefore, coaches and sport scientists should consider this when they are designing their sided game drills during the training microcycle (16). Instead, accelerations were not found to be different among positions (Figure 5, $p = 0.115$), which means that all players, independently from their role, have similar mechanical demands. However, this was not the case for the number of decelerations recorded (Figure 6), since ST reported the highest number of events (1.8 n·min^{-1}) compared to the other roles such as CB (1.5 n·min^{-1}, $p < 0.001$) and FB (1.6 n·min^{-1}, $p = 0.026$). Although these results are interesting and show that sided games' deceleration demands are affected by positions, practitioners should be quite careful because the differences are quite small (see Figure 6). Future research should evaluate if different sided game formats chronically improve some specific physical parameters more than others and if players of different positions actually improve differently.

Internal and external load parameters among sided game types (from 2vs2 to 10vs10)

The secondary analysis of this paper assessed the internal and external load parameters among the sided game types.

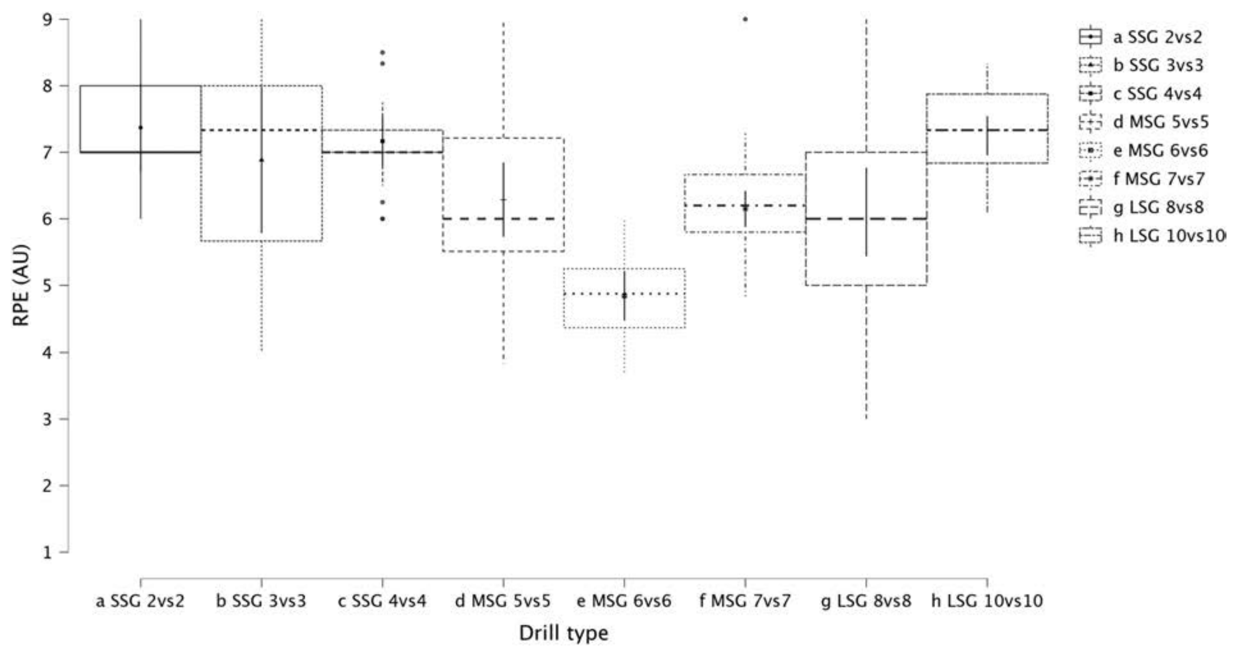

FIGURE 7
Comparison of RPE between drills type (from 2vs2 to 10vs10).

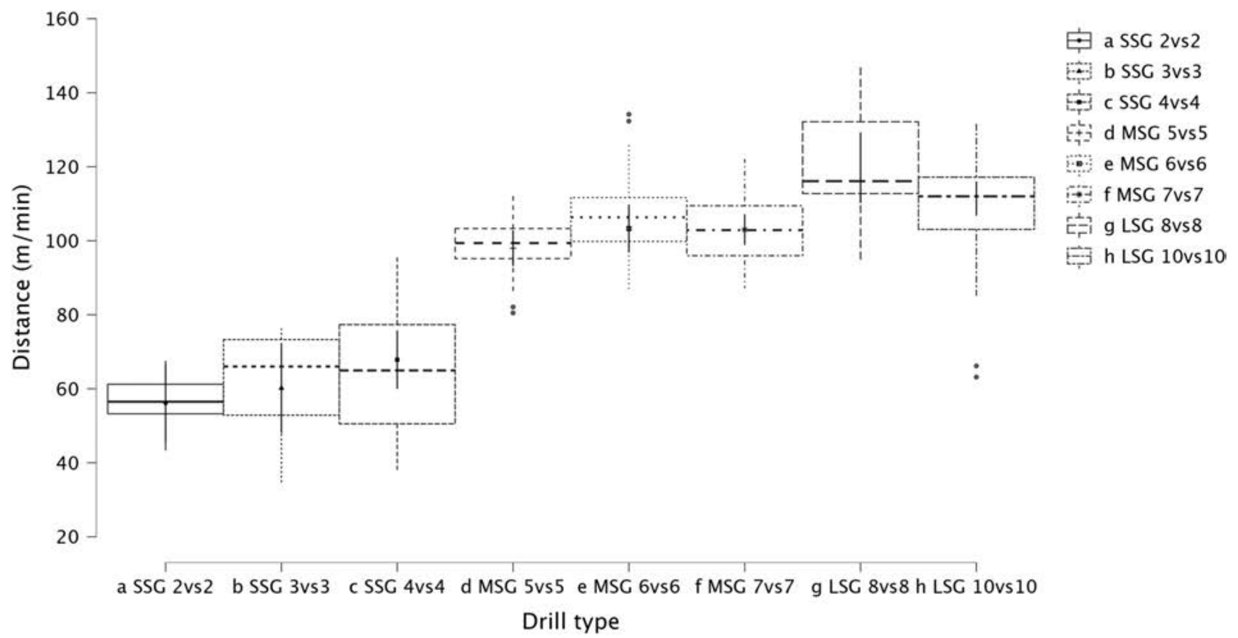

FIGURE 8
Comparison of distance between drills type (from 2vs2 to 10vs10).

We found that RPE score was higher in SSG 2vs2 (RPE = 7.4) compared to MSG 5vs5 (RPE = 6.3, $p = 0.003$), MSG 6vs6 (RPE = 4.8, $p < 0.001$) and MSG 7vs7 (RPE = 6.1, $p < 0.001$) but not compared to LSG 10vs10 (RPE = 7.3, $p = 0.636$). Therefore, coaches should select drills that are very small or very large if they want to increase their players' perceived exertion (**Figure 7**). However, practitioners should understand that the external load parameters among these drills (SSG 2vs2 and LSG 10vs10) are very different. Therefore, the consequent mechanical and physiological adaptations will also be different although they have similar RPE values. As reported in **Figure 8**, LSG 10vs10 (111.4 $m \cdot min^{-1}$) reported the greater distance per minute among sided game types and in particular they have nearly

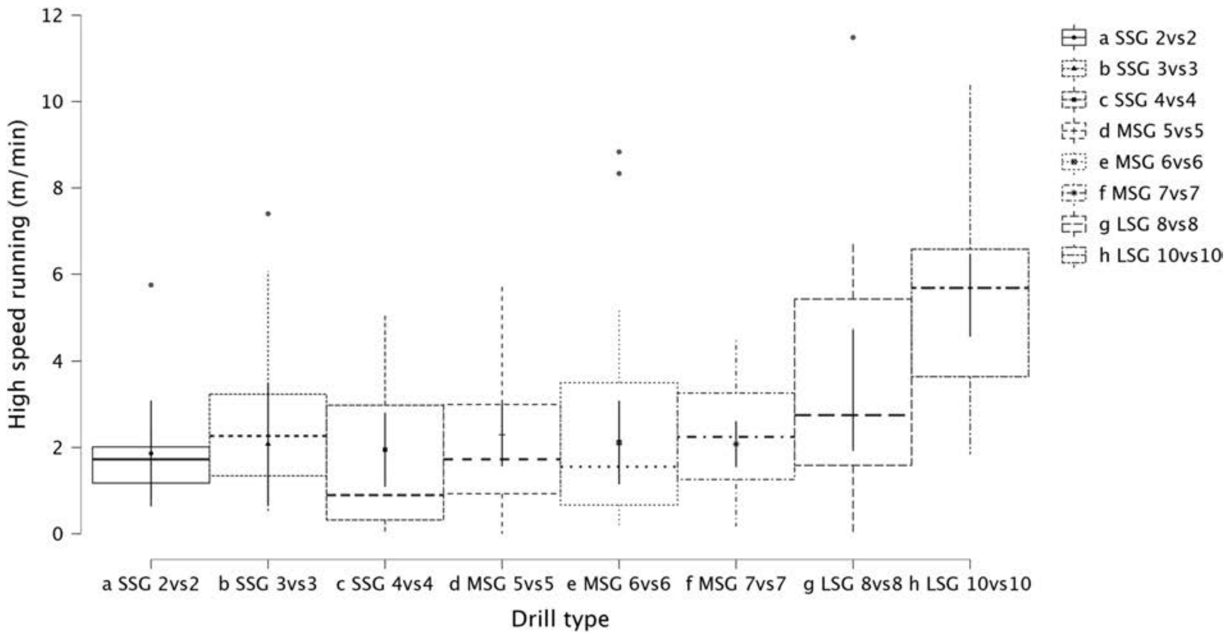

FIGURE 9
Comparison of HSR distance between drills type (from 2vs2 to 10vs10).

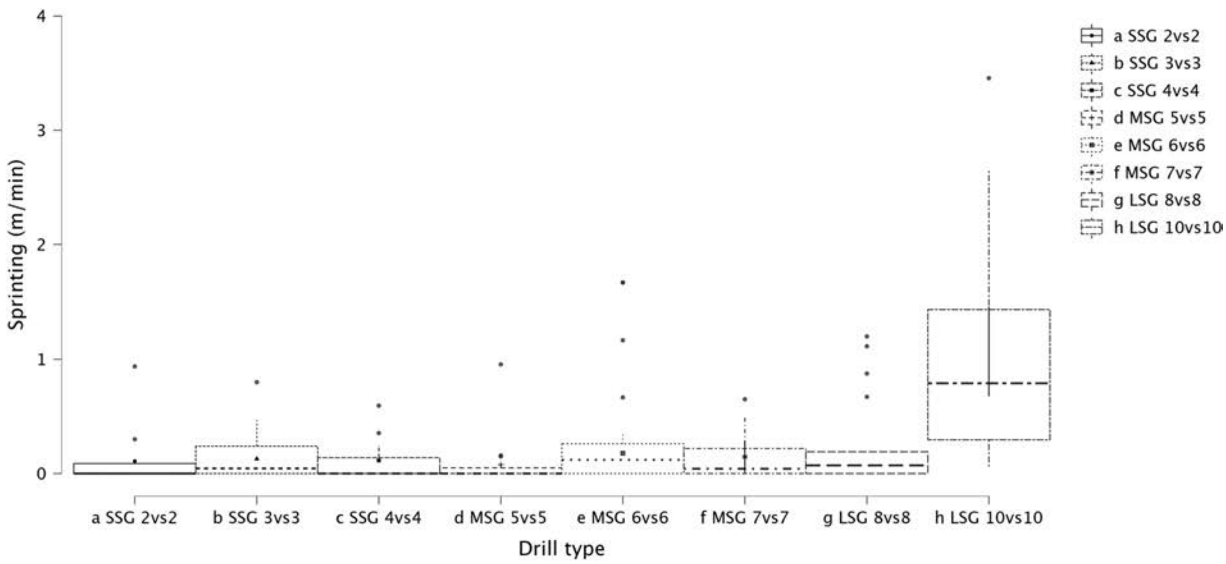

FIGURE 10
Comparison of sprinting distance between drills type (from 2vs2 to 10vs10).

twice the value compared to SSG 2vs2 (56.1 m·min^{-1}). Previous literature reported that professional players of a similar level (English Football League One) covered a distance per minute of 106 m·min^{-1} during official matches (39). Therefore, all drills above 100 m·min^{-1} reported in **Figure 8** (i.e., MSG 6vs6, MSG 7vs7, LSG 8vs8 and LSG 10vs10) would be suitable to replicate the demands of the match for these players (English League One level). However, the intensity per minute recorded in other leagues is higher than what is reported here, so practitioners should verify that their drills obtain the desired intensity (40, 41). Regarding HSR, LSG10vs10 and LSG 8vs8 (**Figure 9**) are the most demanding drills, for instance they had a mean intensity of 5.5 m·min^{-1} and 3.3 m·min^{-1}, respectively, which is *largely* different ($p < 0.001$) compared to any SSG formats. Moreover, when the sprinting distance was assessed, LSG10vs10 were the only format which actually reported an intensity greater than 1 m·min^{-1}

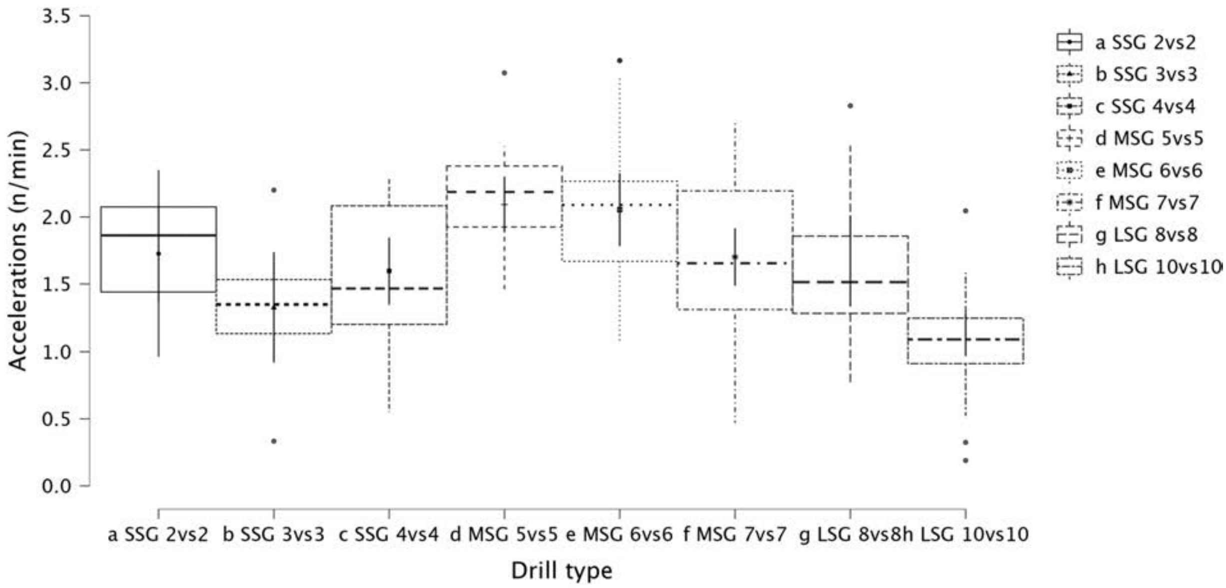

FIGURE 11
Comparison of acceleration number between drills type (from 2vs2 to 10vs10).

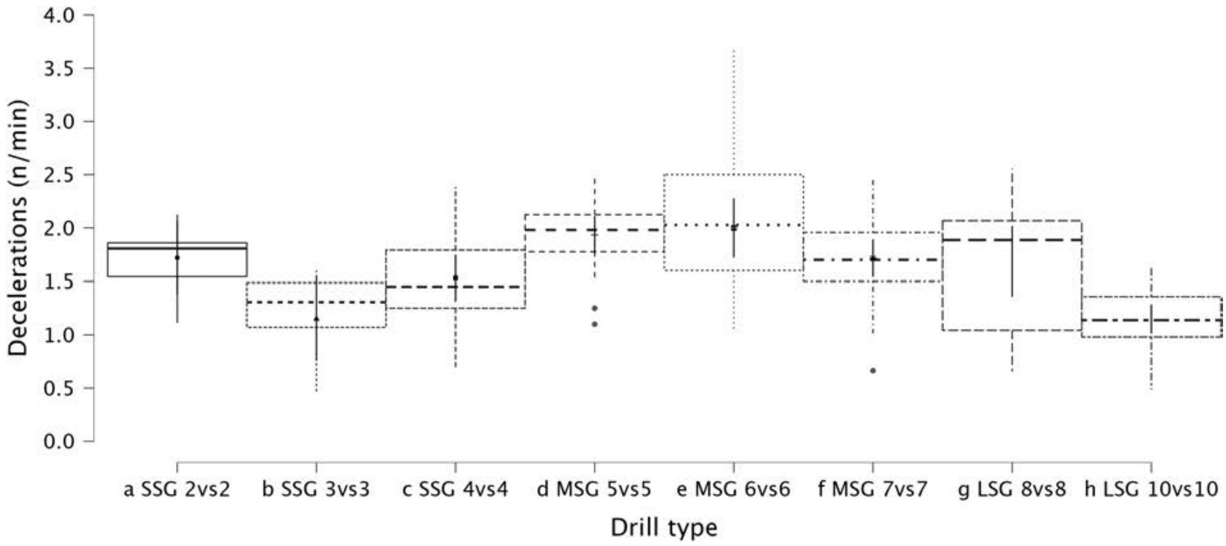

FIGURE 12
Comparison of deceleration number between drills type (from 2vs2 to 10vs10).

(**Figure 10**). Therefore, LSG10vs10 is the only format that is recommended to be used when coaches want to develop sprinting with their players. However, we should be aware that the overall sprinting dose is limited and may not be sufficient to achieve the aim (2, 17, 33, 42, 43). Contrariwise, regarding accelerations and decelerations, the most suitable drills for training purposes are MSG 5vs5 and MSG 6vs6, respectively (Figures **11**, **12**). Overall, MSG formats (i.e., 5vs5 and 6vs6) seem to offer a valid acceleration and deceleration frequencies $>2\ n \cdot min^{-1}$. Therefore, coaches and sports scientists could use these sided games to stimulate acceleration and deceleration training doses in their players (10).

Limitations and future directions

This study has some limitations, first, the sample enrolled in this study is a professional team in the English League One; therefore, higher or lower-level players could present different internal and external load demands compared to the ones reported here as well as coaches of other clubs could differently influence these drills with their encouragement. Second, only male players were assessed in this study; therefore, these results should be replicated with female football players to verify that what is reported here can be extended to female populations. Moreover, recent research reported that the use of individualized players' speed thresholds (e.g., sprinting speed or maximal aerobic speed) could be helpful in training load monitoring. An individualization based on the peak speed (e.g., recorded by GNSS) was not performed in this study, therefore, future research could investigate if this approach can offer additional insights (2, 17, 44). Lastly, this study did not consider any metabolic load parameter (e.g., metabolic power) or heart rate (45, 46). Future studies could verify whether these parameters differ among-sided game formats (SSG, MSG, and LSG) or if players' positions influence them.

Conclusions

This study found that internal (i.e., RPE) and external load parameters (e.g., accelerations and sprinting distance) were different between sided-game formats (SSG, MSG, LSG) in professional football players. Some formats were more suitable to load some specific parameters. For instance, distance per minute was greater during LSG than SSG and HSR, and sprinting distance was greater in LSG compared to SSG. This study found that the number of accelerations and decelerations was higher in MSG compared to SSG and LSG, which could have interesting practical applications for coaches. Moreover, this study found that external load metrics (e.g., HSR and decelerations) were subjective to players' positions. For example, HSR and sprinting distance were greater for ST and FB than CB. However, RPE and distance per minute were not affected by positions. Coaches should be aware of the internal load and external load demands of different game formats (LSG, MSG, and SSG), as well as if players' positions can influence these load parameters that would be critical for training load planning. Finally, this study analyzed the internal and external load parameters among sided-game types (from 2vs2 to 10vs10) and found that LSG 8vs8 was the most demanding drill for distance covered per minute, LSG 10 vs. 10 was the most demanding drill for HSR and sprinting. On the other hand, acceleration and deceleration demands were greater in MSG 5vs5 and MSG 6vs6 compared to other formats. Coaches and sports scientists should consider these findings and select the most appropriate sided-game types during their training.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The Ethics Committee of the University of Suffolk (Ipswich, UK) approved this study (project code: RETHS22/016). The ethics committee waived the requirement of written informed consent for participation.

Author contributions

MB wrote the first draft of the paper and made the first data analysis; AJC recorded the data used in this paper; MB and AJC conceptualized the paper and reviewed the manuscript; JP and JV contributed to the data analysis and reviewed the manuscript. All authors contributed to the article and approved the submitted version.

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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.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2023.1165242/full#supplementary-material.

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