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Injury incidence and risk factors in youth soccer players: a systematic literature review. Part I: epidemiological analysis

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ABSTRACT: The analysis of the epidemiological data and the risk factors underlying injuries is crucial to promote prevention strategies in young soccer players. The objective of the present study was to perform a systematic literature review on the epidemiological data, described in the first part, and injury risk factors, presented in the second part. After electronic database searching, articles in line with the inclusion criteria were selected for the systematic review. Epidemiological data were extracted and discussed in this first part of the review. Data were grouped as follows: injury incidence, injury severity, and re-injury, injury types, injury mechanisms, and anatomical location. The principal findings of this first part of the review are as follows: (1) injury incidence is higher in older players and during matches than during training; (2) sex and maturity status may increase risk of injury; (3) male soccer players are more prone to muscle strains and ligament sprains while female players suffer more ligament sprains; (4) most injuries are located in the ankle and thigh in young male soccer players, and in the ankle and knee in female players; (5) severe injuries are less frequent but the incidence increases in older players. Re-injuries represent only a small percentage. Although soccer is considered a safe sport, many injuries are recorded in young soccer players every year. Injury predisposition changes in relation to age, sex, and biological age. Coaches and physical trainers should be aware of individual differences in order to promote prevention strategies and personalised training.

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INTRODUCTION

Football (soccer) is the most popular sport in the world, as witnessed by both the huge TV audience and more than 260 million people actively involved in playing it [1], also encouraged by the health benefits obtained by regular recreational practice. In fact, recreational soccer has been demonstrated to have positive effects on cardiovascular function, body composition, and neuromuscular fitness [2–5]. Moreover, according to the 2016 FIFA report, more than half of the 38 million players officially registered belong to the youth category under 18 years. Although youth soccer seems to be a healthy and relatively safe sport [6–8], adolescent players are constantly exposed to risks of injury. Indeed, soccer is a contact sport characterised by high-intensity activities such as sprints, jumps, and changes of direction [9] that could raise the players' predisposition to injury. Furthermore, financial rewards and the signing of a professional contract may contribute to increasing the state of stress and anxiety of youth players [10].

Trauma in youth athletes could produce various side effects, such as dropout [11], alteration in the talent development process,

long-term sequelae [12], and an economic impact on the health care system [13]. Therefore, understanding the epidemiological data and risk factors underpinning the injury mechanism is crucial. Acquiring such awareness requires a complex analysis due to the numerous elements which may determine the occurrence of an injury. In the sports science literature, many risk factors linked to injuries are commonly categorised in extrinsic (e.g. training load, rules, playing surface) and intrinsic (e.g. flexibility, strength, age, sex, previous injury) factors [14].

Moreover, unlike adults, during biological maturation young athletes experience a time of their life characterised by rapid changes in hormonal release, body size, shape, composition [15], and neuromuscular control [16]. All these factors make young soccer players highly predisposed to the risk of injury. Thus, the analysis of epidemiological data and injury risk factors of youth soccer players is highly needed in order to promote effective prevention strategies. Indeed, according to "the sequence of prevention" introduced by Van Mechelen et al. [17], before applying preventive measures, it is

needed to analyse sports injuries (e.g. incidence, severity) and to recognise the underlying risk factors. Therefore, the current systematic literature review aimed to improve this knowledge, providing adequate information to practitioners in order to implement robust preventive strategies.

To date, many epidemiological studies have been carried out in a young soccer population, although the use of different injury definitions, age of samples involved, competition level, and length of follow-up, makes the interpretation of these results difficult. Among the total amount of epidemiological studies, some of these have focused on injury incidence, type, anatomical distribution, or severity [18–22], while others have investigated the risk factors [23–27].

Moreover, several authors have tried to review data on injuries in youth soccer players, but some of these studies are dated [28] or

exclusively focused on descriptive epidemiological data [29, 30]. Then, only information about injury incidence and distribution is not enough to understand the suitable prevention strategy in young soccer.

Based on our knowledge, to date, there are no systematic literature reviews that combine epidemiological data with injury risk factors. Therefore, the purpose of the present review is to summarise the evidence related to injury incidence in young soccer players and to match it with the risk factors, in order to understand the mechanism underlying a higher injury predisposition, promote prevention strategies and minimise lost playing time. The present review is organised in two different parts:

- Part 1: epidemiological data review of the injuries in young soccer players.
- Part 2: analysis of the injury risk factors in young soccer players.

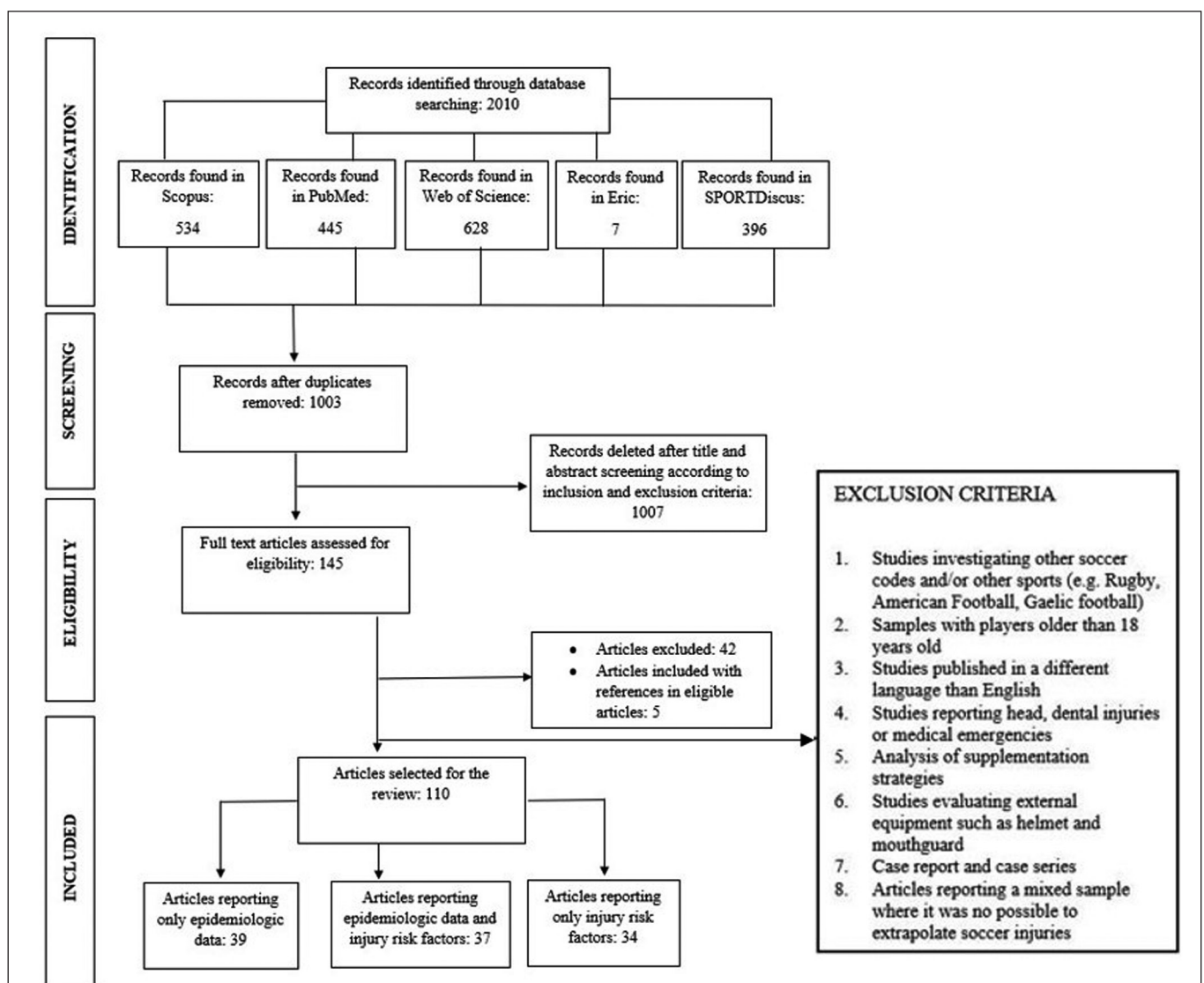


FIG. 1. PRISMA Flow Chart.

MATERIALS AND METHODS

Search strategy

A systematic review of the literature was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [31]. The whole research (composed of two parts) aimed at identifying studies concerning injury epidemiological data and injury risk factors in youth soccer players. The eligible studies were searched by two independent researchers consulting the following electronic databases: ERIC (Educational Resources Information Center), PubMed/NCBI (National Center for Biotechnology Information, U.S. National Library of Medicine), Scopus, SPORTDiscus via EBSCOhost and Web of Science (WOS), from inception to October 2019. In each database, the search was performed as follows: [soccer OR football] AND [youth OR young OR adolescen*] AND [injur* OR risk of injury OR impairments].

All the articles were collected using Excel Software (Microsoft Excel 2016, Microsoft Corporation, Washington, USA) to manage duplicates and screening procedures.

Inclusion and exclusion criteria

The systematic literature review focused on two main topics: injury epidemiological data and injury risk factors in youth soccer players; thus, the inclusion criteria were general and specific for each topic.

General inclusion criteria: (1) published original data (i.e., abstracts, books, reviews, systematic reviews, and meta-analyses were excluded); (2) published in the English language; (3) published in

a peer-review scientific journal; (4) articles found on the electronic database up to the 28th of February 2021. Finally, to allow the identification of relevant papers not found during the electronic search, the snowballing technique was applied.

Inclusion criteria for injury epidemiological data: (1) samples of young male and female soccer players (7–18 years old); (2) articles which collected at least one outcome related to injury epidemiological data: injury incidence, injury type, severity, re-injury, anatomical location (3) prospective or retrospective studies.

Inclusion criteria for injury risk factors: (1) samples of young male and female soccer players (5–18 years old); (2) articles that analysed risk factors connected to the onset of injury (3) articles identifying injury predisposition factors (4) prospective, retrospective, cross-sectional studies, randomised control trials (RCT).

Exclusion criteria are presented in Figure 1.

Study selection process

Electronic database searching was initially performed by one reviewer (MM). Then, removal of duplicates was done by two reviewers (MM and AT). After this step, considering the high amounts of articles identified, a preliminary title screening was conducted, and the selected articles were subjected to abstract screening according to the inclusion criteria previously mentioned.

The full text of the articles identified for eligibility were analysed by three reviewers (AT, MG, MM) for the two main topics: injury epidemiological data and injury risk factors. Thus, the included

TABLE 1. General information of studies selected.

REFERENCES	STUDY DESIGN(QUALITY SCORE)	P1	P2	P3	P4	P5	P6	COUNTRY	DURATION OF DATA COLLECTION	LEVEL OF YOUNG PLAYERS	SEX OF PLAYERS
Andreasen et al. [55]	Prospective injury report (2)	1	0	0	1	0	0	Denmark	5-day tournament	Non-elite	Male/Female
Aoki et al. [26]	Prospective cohort study (4)	1	1	0	1	0	1	Japan	1 season	Non-elite	Male
Bacon and Mauger [80]	Prospective cohort study (5)	1	0	1	1	1	1	UK	2 seasons	Elite	Male
Bianco et al. [67]	Prospective cohort study (6)	1	1	1	1	1	1	Italy	1 season	Elite	Male
Blazkiewicz et al. [38]	Retrospective, cross sectional study(3)	0	1	0	1	0	1	Poland	Not available	Non-elite	Male
Bowen et al. [23]	Prospective cohort study (6)	1	1	1	1	1	1	UK	2 seasons	Elite	Male
Brink et al. [8]	Prospective cohort study (5)	1	1	0	1	1	1	The Netherlands	2 seasons	Elite	Male
Brito et al. [22]	Prospective cohort study (4)	1	1	0	1	0	1	Portugal	1 season	Non-elite	Male
Brito et al. [46]	Prospective cohort study (5)	1	1	1	1	1	0	Portugal	Preseason (6 weeks)	Sub-elite	Male
Bult et al. [27]	Prospective cohort study (6)	1	1	1	1	1	1	The Netherland	3 seasons	Elite	Male
Cezarino et al. [64]	Prospective cohort study (6)	1	1	1	1	1	1	Brazil	1 season	Elite	Male
Clausen et al. [87]	Prospective cohort study (4)	1	1	0	1	0	1	Denmark	1 season	Non-elite	Female
Cloke et al. [95]	Prospective cohort study (5)	1	1	0	1	1	1	UK	6 seasons	Elite	Male
Cloke et al. [37]	Prospective cohort study (5)	1	1	0	1	1	1	UK	3 seasons	Elite	Male
De Ridder et al. [74]	Prospective cohort study (5)	1	1	0	1	1	1	Belgium	3 seasons	Elite	Male
Deehan et al. [18]	Prospective cohort study (5)	1	1	0	1	1	1	UK	5 seasons	Elite	Male
Del Coso et al. [45]	Retrospective cohort study (3)	0	1	0	1	0	1	Spain	1 season	Non-elite/National	Female
Elias [35]	Prospective injury report (4)	1	1	0	1	0	1	USA	10 years (tournament)	Non-elite	Male/Female
Emery & Meeuwisse [84]	Prospective cohort study (3)	1	1	0	1	0	0	Canada	20 weeks	Non-elite	Male/Female
Emery et al. [72]	Prospective cohort study (4)	1	1	1	1	0	0	Canada	13 weeks	Non-elite	Male/Female
Ergun et al. [43]	Prospective cohort study (6)	1	1	1	1	1	1	Turkey	3 seasons	Elite	Male
Frisch et al. [70]	Prospective cohort study (5)	1	1	1	1	0	1	Luxemburg	1 season	Non-elite	Male

TABLE 1. Continue.

REFERENCES	STUDY DESIGN(QUALITY SCORE)	P1	P2	P3	P4	P5	P6	COUNTRY	DURATION OF DATACOLLECTION	LEVEL OF YOUNGPLAYERS	SEX OF PLAYERS
Froholdt et al. [78]	Prospective cohort study (5)	1	1	1	1	0	1	Norway	1 season	Non-elite	Male/Female
Hägglund & Waldén [82]	Prospective cohort study (4)	1	1	0	1	0	1	Sweden	1 season	Non-elite	Female
Herdy et al. [52]	Descriptive cross-sectional and correlational study (4)	0	1	0	1	1	1	Brazil	11 months	Elite	Male
Hoff & Martin [79]	Retrospective survey (3)	0	1	0	1	0	1	USA	Not available	Non-elite	Male/Female
Jacobs & Van Den Berg [53]	Retrospective cohort study (4)	0	0	1	1	1	1	Africa	Not available	Elite	Male
Johnson et al. [77]	Prospective cohort study (4)	1	0	0	1	1	1	UK	6 season	Elite	Male
Johnson et al. [73]	Prospective cohort study (5)	1	1	0	1	1	1	UK	2 season	Elite	Male
Kakavelakis et al. [56]	Prospective cohort study (5)	1	1	1	1	0	1	Greece	1 season	Non-elite	Male
Kemper et al. [69]	Prospective cohort study (5)	1	1	0	1	1	1	The Netherlands	1 season	Elite/Non-elite	Male
Khodaei et al. [51]	Descriptive epidemiological study (4)	1	1	0	1	0	1	USA	9 seasons	Non-elite	Male/Female
Kofotolis [68]	Prospective cohort study (4)	1	1	0	1	0	1	Greece	1 season	Non-elite	Male
Kolstrup et al. [7]	Prospective cohort study (5)	1	1	0	1	1	1	Denmark	3 seasons	Elite	Male/Female
Kucera et al. [76]	Prospective cohort study (4)	1	1	0	1	0	1	USA	4 seasons	Non-elite	Male/Female
Kuzuhara et al. [21]	Prospective cohort study (4)	1	1	0	1	0	1	Japan	1 season	Non-elite	Male
Le Gall et al. [42]	Prospective cohort study (6)	1	1	1	1	1	1	France	10 seasons	Elite	Male
Le Gall et al. [71]	Prospective cohort study (6)	1	1	1	1	1	1	France	10 seasons	Elite	Male
Light et al. [63]	Prospective cohort study (6)	1	1	1	1	1	1	UK	4 seasons	Elite	Male
Lislevand et al. [49]	Prospective cohort study (3)	1	1	0	1	0	0	Norway	2-day tournament	Non-elite	Female
Maehlum et al. [41]	Prospective cohort study (2)	1	0	0	1	0	0	Norway	6-day tournament	Non-elite	Male/Female
Materne et al. [62]	Prospective cohort study (6)	1	1	1	1	1	1	Qatar	4 seasons	Elite	Male
Materne et al. [97]	Prospective cohort study (6)	1	1	1	1	1	1	Qatar	4 seasons	Elite	Male
McCarroll et al. [54]	Prospective cohort study (2)	1	0	0	1	0	0	USA	4 months	Non-elite	Male/Female
Nagle et al. [92]	Prospective cohort study (5)	1	1	1	1	0	1	USA	8 seasons	Non-elite	Male/Female
Namazi et al. [91]	Prospective cohort study (5)	1	1	0	1	1	1	Iran	1 season	Elite	Male
Nilsson et al. [48]	Prospective cohort study (6)	1	1	1	1	1	1	Sweden	2 seasons	Elite	Male
Nogueira et al. [44]	Prospective cohort study (5)	1	1	1	1	0	1	Portugal	6 months	Non-elite	Male
O'Kane et al. [88]	Prospective cohort study (5)	1	1	0	1	1	1	USA	2 seasons	Elite	Female
O'Kane et al. [116]	Prospective cohort study (5)	1	1	0	1	1	1	USA	2 seasons	Elite	Female
O'Kane et al. [85]	Prospective cohort study (5)	1	1	0	1	1	1	USA	2 seasons	Elite	Female
Olumide & Ajide [19]	Prospective cohort study (4)	1	1	1	1	0	0	Nigeria	3-day tournament	Non-elite	Male
Price et al. [96]	Prospective cohort study (5)	1	1	1	1	0	1	UK	2 seasons	Non-elite	Male
Raya-González et al.[66]	Prospective cohort study (6)	1	1	1	1	1	1	Spain	4 seasons	Elite	Male
Raya-González et al.[50]	Prospective cohort study (6)	1	1	1	1	1	1	Spain	1 season	Elite	Male
Raya-González et al.[25]	Prospective cohort study (5)	1	1	0	1	1	1	Spain	1 season	Elite	Male
Read et al. [36]	Prospective cohort study (6)	1	1	1	1	1	1	UK	1 season	Elite	Male
Renshaw & Goodwin [47]	Prospective cohort study (6)	1	1	1	1	1	1	UK	1 season	Elite	Male
Rosenbaum et al.[93]	Prospective cohort study (3)	1	1	0	1	0	0	USA	2-day tournament	Non-elite	Male/Female
Rössler et al.[59]	Prospective cohort study (5)	1	1	1	1	0	1	Czech Republic and Switzerland	2 seasons	Non-elite	Male/Female
Rössler et al. [83]	Prospective cohort study (5)	1	1	1	1	0	1	Czech Republic and Switzerland	2 seasons	Non-elite	Male/Female
Schiff et al. [58]	Prospective cohort study (4)	1	1	0	1	0	1	USA	1 season	Non-elite	Female
Schiff [57]	Cross-sectional survey (3)	0	1	0	1	0	1	USA	Not available	Non-elite	Female
Schmidt-Olsen et al. [20]	Prospective cohort study (5)	1	1	0	1	1	1	Denmark	1 season	Elite	Male
Sieland et al. [94]	Prospective cohort study (6)	1	1	1	1	1	1	Germany	2 seasons	Elite	Male
Sokka et al. [65]	Prospective cohort study (4)	1	1	1	1	0	0	Finland	20 weeks	Non-elite	Male/Female
Soligard et al. [24]	Prospective cohort study (4)	1	1	0	1	0	1	Norway	1 season	Non-elite	Female
Steffen et al. [86]	Prospective cohort study (4)	1	1	0	1	0	1	Norway	1 season	Non-elite	Female
Sullivan et al. [40]	Prospective cohort study (4)	1	1	0	1	0	1	USA	Not available	Non-elite	Male/Female
Timpka et al. [12]	Prospective cohort study (4)	1	1	0	1	0	1	Sweden	1 season	Non-elite	Male
Tourny et al. [39]	Prospective cohort study (4)	1	0	0	1	1	1	France	3 seasons	Elite	Male
Van der Sluis et al. [89]	Prospective cohort study (5)	1	1	0	1	1	1	The Netherlands	3 seasons	Elite	Male
Van der Sluis et al. [75]	Prospective cohort study (5)	1	1	0	1	1	1	The Netherlands	3 seasons	Elite	Male
Volpi et al. [60]	Prospective cohort study (5)	1	1	0	1	1	1	Italy	4 years	Elite	Male
Watson et al. [81]	Prospective cohort study (3)	1	1	0	1	0	0	USA	20 weeks	Non-elite	Female
Watson et al. [90]	Prospective cohort study (3)	1	1	0	1	0	0	USA	20 weeks	Non-elite	Female
Wik et al. [61]	Prospective cohort study (6)	1	1	1	1	1	1	Qatar	4 seasons	Elite	Male

articles were organised separately according to the area of interest and subjected to a data extraction process conducted by two reviewers (AT, MM).

Article quality assessment

As highlighted in a previous systematic review [32], Delphi [33] or PEDro (Physiotherapy Evidence Database) [34] scales, which are commonly used to assess article quality, present criteria that are not relevant for specific studies, as in the current review. Following the same procedure reported by Hume et al. [32], two authors (MM, AT) independently assessed each article reported in the current review using a 6-item custom methodological quality assessment scale. The six items were (P1) study design (0 = retrospective cohort study, 1 = prospective cohort study); (P2) injury definition (0 = not reported, 1 = reported); (P3) injury severity (0 = not reported, 1 = reported); (P4) sample size (0 = less than 20 subjects recruited, 1 = more than 20 subjects recruited); (P5) participants' level (0 = non-elite, 1 = elite/sub-elite); (P6) follow-up period (0 = less than six months, 1 = more than six months). The evaluation process together with the final quality score are presented in Table 1. The quality score calculated was not considered as an exclusion criterion.

RESULTS

Search results

The articles' selection process is illustrated in the Prisma Flow Chart (Figure1). A total of 110 articles were included in the present systematic literature review in accordance with inclusion and exclusion criteria. Of the 110 articles included, thirty-nine reported only epidemiological data [7, 12, 18–22, 35–66] and thirty-seven combined epidemiological data and injury risk factors [8, 23–27, 67–97]. The remaining articles, reporting only injury risk factors, are discussed in the second part of the current systematic review.

The main findings extracted about epidemiological data and presented in this part 1 have been organised based on the following parameters: injury incidence, injury severity and re-injury, injury types, injury mechanisms, and anatomical location. General information of the studies, including the article quality assessment score, is presented in Table 1.

Epidemiological data

Injury definition and collection process

The studies included in the review were characterised by different injury definitions. Thirty-six articles were based on Fuller et al.'s [98] consensus statement published in 2006 [7, 8, 12, 19, 22–24, 26, 27, 43–49, 58, 59, 61–65, 67, 69, 75, 78, 82, 86–91, 93, 97]. Regarding the time loss from soccer activity, eight studies used more than 48 h [18, 36, 37, 42, 71, 74, 95, 96], four studies up to 24 h [51, 56, 57, 92] and only one study used a period of four weeks [96]. Three studies followed Hägglund et al.'s [99] indications [25, 50, 66]. Ten studies defined overall injury as inability to

take part in training or competition [21, 38, 40, 68, 70, 72, 73, 76, 79, 84]. Two articles used an acute or overuse definition [85, 90]. The remaining studies did not report [39, 41, 53–55, 77, 80] or used a different injury definition [35, 52].

Moreover, different injury collection strategies were adopted. Most of the studies relied on physiotherapists/medical staff [7, 8, 18, 22, 23, 25, 27, 35–37, 39, 41–49, 52, 55, 60–64, 67–69, 71–75, 78, 80, 82, 89, 91, 93–97, 100]; others, instead, relied on the coaching staff [12, 21, 22, 24, 26, 40, 44, 50, 54, 58, 59, 66, 86, 87, 92, 93], the research team [19, 70, 90] or a self-reported questionnaire/web system/phone interview [38, 51, 53, 56, 57, 65, 76, 79, 83–85, 88, 90]. Two studies did not report any information [20, 77].

Injury incidence

The injury incidences reported below were calculated as the ratio between the number of injuries and hours of playing exposure per 1000 h. In total, fifty-five articles [7, 8, 12, 18–23, 25–27, 35–37, 39–44, 46–48, 50–53, 56, 61, 63–78, 80, 83, 84, 89, 91–95] reported injury incidence in young male soccer players. The authors identified an overall injury incidence per 1000 h ranging from 0.51 [40] to 18.4 [43]. Specifically, the injury incidence ranged from 2.84 [8] to 47.7 [43] during matches and from 0.9 [22] to 11.14 [8] during training. Three studies, rather than injury incidence, reported injury prevalence, as shown in Table 2 [18, 47, 53]. Moreover, the injury incidence according to chronological age is also reported in Table 2.

Four studies [71, 73, 75, 77] reported injury incidence according to players' biological age and three [27, 73, 89] according to peak height velocity (PHV). Instead, one study adopted the Khamis-Roche equation [63]. Five studies [7, 19, 35, 41, 93] recorded injury incidence during tournaments with an injury rate ranging from 7.26 [93] to 113.6 [19].

In the articles reporting female injuries [7, 24, 35, 40, 41, 45, 49, 51, 57, 65, 72, 76, 78, 82, 85, 87, 90, 92, 93] the overall injury incidence ranged between 1.1 [40] and 7.20 [65]. During training the value varied from 0.74 [92] to 3.47 [65], whereas during matches it varied from 2.88 [92] to 30.59 [65]. Four studies [7, 35, 41, 49] recorded injury data during a female tournament.

Injury incidence for specific cases (e.g. ankle injuries, non-contact injuries, traumatic injuries) is presented in Table 2.

Injury incidence according to participants' level

Epidemiological information was also extracted and discussed according to participants' level. In elite young male soccer players, an overall injury incidence ranging from 1.23 [50] to 12.1 [23] was reported. In non-elite young male soccer players, the range was from 0.51 [40] to 10.4 [70]. Specifically, a training injury rate from 0.72 [50] to 11.14 [8] in elite young soccer players, and from 0.58 [92] to 7.1 [70] in non-elite young soccer players were identified. Concerning match injury rate, the range was from 2.84 [67] to

TABLE 2. Injury incidence summary in young soccer players.

References	Category (participation level)	Maturity	Number of players	Number of Injuries	Average Injury per player (player/n injury)	Injury incidence per 1000 h (prevalence %)			
						Training	Matches	Tournament	Overall
Male									
Elias [35]	U12-U19 (Non-elite)		89500	2353				13.39	
	U12			298				11.22	
	U14			606				11.81	
	U16			789				16.05	
Wik et al. [61]	U13-U18 (Elite)		591	1111	1.9	8.2	32.0		12.0
	U13		102	133		6.0	21.2		7.8
	U14		106	164		6.3	23.4		8.5
	U15 U16		117	194		7.4	27.8		10.9
	U17		102	215		8.8	35.9		13.7
	U18		92	234		11.0	43.8		17.0
			72	171		13.2	40.0		18.6
	U19			625					13.46
Light et al. [63]	U9-U21 (Elite)		190	603					2.4
	U9								1.8
	U10								2
	U11								0.7
	U12								1.1
	U13								3
	U14								2.9
	U15								2.5
	U16								2.3
	U18								2.9
	U21								4.8
Materne et al. [97]	U13-U19		454	1565		736 (47.1%)	829 (52.9%)		
		Mature	94	395		209 (52.9%)	186 (47.1%)		
		Early maturers	192	692		300 (43.4%)	392 (56.6%)		
		Normal maturers	158	446		205 (46%)	241 (54%)		
		Late maturers	10	32		22 (68.8%)	10 (31.3%)		
Bianco et al. [67]	U13-U20 (Elite)		80	107		1.15	2.84		1.28
	U13-U16		54	72		1.16	2.20		1.22
	U17-U20		23	35		1.13	4.30		1.40
Bowen et al. [23]	U18-U21 (Elite)		32	138		7.9	33.5		12.1
Deehan et al. [18]	U9-U19 (Elite)		210	685	0.6	334 (49%)	351 (41%)		
Read et al. [36]	U11-U18 (Elite)		609	804					1.32
	U11		83	53					0.64
	U12		88	96					1.09
	U13		83	102					1.23
	U14		90	97					1.08
	U15		71	111					1.56
	U16		86	116					1.35
	U18		107	229					2.14
Cloke et al. [37] ^a	U9-U18 (Elite)		419	56		0.077	0.862		0.342
Cezarino et al. [64]	U11-U20 (Elite)		228	187		1.41	8.17		1.86
	U11		23	2		0.22	2.72		0.41
	U12		22	8		2.05	NA		1.80
	U13		25	6		0.40	5.47		0.74
	U14		28	21		1.37	9.09		1.64
	U15		28	12		0.81	2.65		0.91
	U16		25	27		2.05	4.58		2.18
	U17		28	46		2.28	13.66		3.05
	U18		16	18		1.42	8.08		1.74
	U20		33	47		1.32	22.48		2.46
Sokka et al. [65]	U9-U14 (Non-elute)		567	321		3.63	24.67		6.29
Kofotolis et al.[68] ^a	U9-U15 (Non-elite)		677	38					0.38
Kemper et al. [69]	U12-U19 (Elite/Non-elite)		101	134		3.3	18.2		5.9
Frisch et al. [70]	U15-U19 (Non-elite)		67	163		7.1	23.5		10.4

TABLE 2. Continue.

References	Category (participation level)	Maturity	Number of players	Number of Injuries	Average Injury per player (player/n injury)	Injury incidence per 1000 h (prevalence %)			
						Training	Matches	Tournament	Overall
Le Gall et al. [71]	U14 (Elite)		233	588	2.5	4.7	11.8		5.6
		Early maturers	57	146	2.6	4.5	13.2		5.7
		Normal maturers	148	384	2.6	4.8	12.3		5.8
		Late maturers	28	58	2.1	4.3	6.5		4.6
Timpka et al. [12]	U14-U17			44					2.4
	U14 (Non-elite)			9					1.7
	U15 (Non-elite)			0					0
	U15 (elite)			16					6.8
	U16 (Non-elite)			4					1.5
	U16 (Elite)			9					2.8
	U17 (Elite)			6					1.9
Błażkiewicz et al. [38] ^b	U12-U18 (Non-elite)		33	52					6.48
Raya-González et al. [25] ^c	U19 (Elite)		22	27		3.87	14.35		5.11
Tourny et al. [39]	U12-U20 (Elite)		412	596					
	U12		38			1.0	9.4		1.5
	U13		53			2.2	16.5		2.8
	U14		57			2.3	28.7		4.1
	U15		51			2.8	36.7		5.0
	U16		52			2.2	29.4		3.7
	U17		52			3.6	24.1		4.8
	U19		51			2.8	30.3		4.4
	U20		58			3.8	42.2		5.7
Sullivan et al. [40]	U8-U19 (Non-elite)		931	19					0.51
Emery et al. [72]	U14-U18 (Non-elite)		317	39					5.55
	U14			16					7.88
	U16			16					5.68
	U18			7					3.22
Maehlum et al. [41]	U12-U18 (Non-elite)			266				9.9	
	U12							9.3	
	U13							9.1	
	U16							11.2	
	U18							8.6	
Johnson et al. [73]	U11-U16 (Elite)		76	88			15.8		
	U11		24	6			7.3		
	U12		21	12			13.4		
	U13		22	16			17.1		
	U14		15	23			22.2		
	U15		16	20			16.0		
	U16		14	11			17.0		
		Pre-PHV					11.5		
		Circa-PHV					24.5		
		Post-PHV					16.4		
		Early maturers					Not reported		
		Normal maturers					18.5		
		Late maturers					6.4		
De Ridder et al. [74]	U11-U17 (Elite)		133	68					2.0
Olumide & Ajide [19]	U11-U19 (Non-elite)		90	15				113.6	
Le Gall et al. [42]	U14-U16 (Elite)		660	1152	2.2	3.9	11.2		4.8
	U14		240	420	2.2	4.1	9.5		4.9
	U15		220	361	2.1	3.7	10.4		4.6
	U16		200	371	2.3	3.8	14.2		5.2
Aoki et al. [26]	U14-U16 (Non-elite)		301	425					4.04
Schmidt-Olsen et al. [20]	U13 (Elite)		247	137	0.55				3.4
	U15		112	67	0.60				3.8
	U17		137	108	0.79				4.0
Kolstrup et al. [7]	U12-U19 (Elite)		32380	1091				13.1	

TABLE 2. Continue.

References	Category (participation level)	Maturity	Number of players	Number of Injuries	Average Injury per player (player/n injury)	Injury incidence per 1000 h (prevalence %)			
						Training	Matches	Tournament	Overall
Ergün et al. [43]	U17-U19 (Elite)		24	44		10.5	47.7		18.4
	U17		24	25		14.9	35.9		19.4
	U18		24	5		7.6	45.5		15.2
	U19		24	14		4.8	74.1		18.1
Kuzuhara et al. [21]	U10-U12 (Non-elite)		89	29		1.49	6.43		2.59
Nogueira et al. [44]	U17-U19 (Non-elite)		529	248		2.06	14.22		3.87
	U17		290	138		2.14	12.60		3.74
	U19		239	110		1.97	16.01		4.02
Brito et al. [22]	U13-U19 (Non-elite)		674	199		0.9	4.7		1.2
	U13		179			0.5	2.0		0.6
	U15		169			0.7	6.1		1.1
	U17		165			1.1	3.7		1.4
	U19		161			1.2	7.1		1.7
Brito et al. [46] ^d	U13-U19 (Sub-elite)		912	53		1.8	6.8		2.5
	U13					2.0	1.9		1.9
	U15					2.3	6.3		2.7
	U17					1.4	11.0		2.8
	U19					1.7	7.2		2.4
Kucera et al. [76]	U12-U18 (Non-elite)		928	467					4.3
Renshaw & Goodwin [47]	U9-U18 (Elite)		181	127		64 (50%)	41 (32%)		
Nilsson et al. [48]	U15-U19 (Elite)		43	61	0.7	5.6	15.5		6.8
Bult et al. [27]	U12-U19 (Elite)		170	620	2.0				8.34
	U12		17		1.2				5.86
	U13		50		1.0				5.12
	U14		54		1.6				7.41
	U15		54		2.6				12.44
	U16		53		2.1				8.65
	U17		38		3.1				10.12
	U19		43		2.2				6.90
		Pre-PHV							6.99
Johnson et al. [77]		Circa-PHV							9.56
		Post-PHV							8.66
	U9-U16 (Elite)		292	476		1.44	10.5		2.23
		Early Maturers							1.8
Froholdt et al. [78] ^e		Normal Maturers							1.5
		Late Maturers							1.4
	U6-U16 (Non-elite)		1260	115		0.5	5.4		2.2
Brink et al. [8]	U6-U12		870	44					1.3
	U13-U16		390	71					2.1
	U15-U18 (Elite)		53	320		11.14	37.55		
Raya-González et al. [50] ^f	U14-U19 (Elite)		118	38		0.72	5.63		1.23
	U14		39	8		0.51	4.14		0.91
	U16		39	12		0.48	7.13		1.28
	U19		40	18		1.04	5.05		1.41
Raya-González et al. [66]	U14-U19 (Elite)		309	464		2.10	10.16		2.93
	U14			84		1.95	6.01		2.39
	U16			111		1.88	9.12		2.75
	U19			142		2.07	11.01		2.86
Khodaei et al. [51]	U14-U18 (Non-elite)			2912		1.04	3.68		1.83
Herdy et al. [52]	U11-U20 (Elite)		143	200	1.40				
	U11		30	12	0.40				
	U13		34	15	0.44				
	U15		23	46	2.00				
	U17		24	66	2.75				
	U20		32	61	1.91				
Bacon & Mauger [80]	U18-U21 (Elite)		41	85		3.72	5.84		
Jacobs & Van den Berg [53]	U14-U18 (Elite)		169	544		297 (55%)	247 (45%)		

TABLE 2. Continue.

References	Category (participation level)	Maturity	Number of players	Number of Injuries	Average Injury per player (player/n injury)	Injury incidence per 1000 h (prevalence %)			
						Training	Matches	Tournament	Overall
Rössler et al. [83] ^h	U8-U12 (Non-elite)		6038	417		0.61	4.57		
Emery & Meeuwisse [84]			317	113					5.18
Kakavelakis et al. [56]	U12-U15 (Non-elite)		287	209		3.3	5.6		4.0
Rössler et al. [59] ^h	U8-U12 (Non-elite)		6038	417		0.61	4.57		1.05
	U8		1770	56		0.30	2.49		0.51
	U10		2247	115		0.41	3.59		0.77
	U12		2021	246		1.07	6.14		1.78
Van der Sluis et al. [89]	(Elite)	Pre-PHV				2.57	12.49		
		Circa-PHV				4.19	20.50		
		Post-PHV				3.84	23.08		
Namazi et al. [91]	U18-U21 (Elite)		73	22					2.1
Cloke et al. [95] ^a	U9-U16 (Elite)		14776	2563		1344 (52.4%)	1121 (43.7%)		
Nagle et al. [92]	U14-U18 (Non-elite)			2110		0.58	1.80		0.95
Rosenbaum et al. [93]	U10-U15 (Non-elite)			26				7.26	
Female									
Elias [35]	U12-U19 (Non-elite)		89500	1387				14.78	
	U12			191				12.64	
	U14			439				16.92	
	U16			511				17.68	
	U19			246				10.64	
Soligard et al. [24]	U16 (Non-elite)		202	259		89 (35.5%)	167 (64.5%)		
Sullivan et al. [40]	U8-U19 (Non-elite)		341	15					1.1
Emery et al. [72]	U14-U18 (Non-elite)		317	39					5.62
	U14			20					7.92
	U16			14					5.74
	U18			5					2.53
Maehlum et al. [41]	U14-U18 (Non-elite)			145				17.6	
	U14							13.0	
	U16							20.5	
	U18							15.9	
Kolstrup et al. [7]	U12-U19 (Elite)		13226	740				20.3	
Del Coso et al. [45]	U18 (Elite/Non-elite)		12540	904	0.072				
Kucera et al. [76]	U12-U18 (Non-elite)		555	320					5.3
Lislevand et al. [49]	U13-O16 (Non-elite)		938	123				93.3	
	U13		433	50				116.0	
	U16		213	47				116.6	
	O16		292	26				53.7	
Froholdt et al. [78] ^e	U6-U16 (Non-elite)		619	38		0.4	4.6		2.0
	U6-U12		350	11					1.0
	U13-U16		269	27					1.6
Khodaei et al. [51]	U14-U18 (Non-elite)			3242		1.07	5.25		2.33
Watson et al. [81]	U13-U18 (Non-elite)		54	28					5.3
Häggglund & Waldén [82] ^g	U14-U18 (Non-elite)		4556	96		0.074	1.09		0.35
O'Kane et al. [85] ⁱ	U12-U15 (Elite)		351	83					1.9
Clausen et al. [87] ^g	U15-U18 (Non-elite)		380	34					1.8
Schiff [57]	U11-U14 (Non-elite)		103	44		1.0	6.1		2.2
Nagle et al. [92]	U14-U18 (Non-elite)			2639		0.74	2.88		1.39
Rosenbaum et al. [93]	U11-U18 (Non-elite)			42				7.55	
Sokka et al. [65]	U9-U14 (Non-elite)		163	89		3.47	30.59		7.20

Note: Prevalence was reported in parenthesis (%) preceded by the absolute number

47.7 [43] in elite young soccer players, and from 1.8 [92] to 23.5 [70] in non-elite young soccer players.

By contrast, in non-elite young female soccer players, the overall injury incidence ranged from 0.35 [82] to 17.6 [41]. However, it is necessary to emphasise that the overall injury incidence of 0.35 refers only to knee injuries. Only one study [85] reported the overall injury incidence (1.9) in elite young female soccer players, and also in this case the value reported is limited to overuse injuries.

Severity and re-injury

Twenty-four studies [19, 23, 27, 36, 42–44, 46–48, 50, 53, 56, 59, 65–67, 70–72, 78, 80, 92, 96] reported injury severity in young male soccer players. Nine studies [23, 27, 36, 42–44, 67, 70, 71] recorded the average number of days lost per player. The authors

reported a mean between 7 days [43] and 22 days [23]. Six studies [27, 42, 44, 48, 62, 66] classified minimal (slight) the injuries requiring 1–3 days of recovery. The authors reported a range from 7% [48] to 36% [62] of total injuries. Two studies [43, 70], instead, used 0–3 days as limit, and recorded a prevalence of 47% and 70%, respectively.

Nine studies [24, 36, 42–44, 48, 62, 66, 70] reported minor (mild) injuries requiring 4–7 days of recovery and involved 11% [43] to 29% [42] of the players. Five studies [39, 47, 56, 80, 92] included injuries with a range 0–7 days; the percentage reported was from 7% [47] to 43% [92]. Nine studies [27, 43, 44, 47, 48, 56, 62, 66, 70] classified moderate injuries as needing 8–28 days of recovery. The injuries ranged between 16% [43] and 67% [47]. Two studies [36, 42] based on 1–4 weeks classification, reported 43%

TABLE 3. Injury severity summary in young soccer players. The different lengths of absence employed in the studies were reported.

References	Average n° days lost per player	Minimal Slight	N° days	Minor Mild	N° days	Moderate	N° days	Sever Major	N° Days	Re-injury
Male										
Bianco et al. [67]	14			44 [0.53]	1–6 days	52 [0.62]	7–30 days	11 [0.13]	> 30 days	5 (4.67%)
Bowen et al. [23]	22.1	33 [2.9]	1–3 days	33 [2.9]	4–7 days	45 [3.9]	1–4 weeks	27 [2.4]	> 4 weeks	
Read et al. [36]	21.9	118 (14.7%)	2–3 days	164 (20.4%)	4–7 days	345 (42.9%)	1–4 weeks	177 (22%)	> 4 weeks	
Materne et al. [62]		476 (36%)	1–3 days	246 (18.6%)	4–7 days	377 (28.5%)	8–28 days	233 (16.9%)	> 28 days	
Sokka et al. [65]		166 (51%)	0–3 days	61 (19%)	4–7 days	81 (24%)	8–28 days	24 (6%)	> 28 days	
Frisch et al. [70]	21.4	77 (47.3%)	0–3 days	43 (26.4%)	4–7 days	32 (19.6%)	8–28 days	11 (6.7%)	> 28 days	29 (18%)
Le Gall et al. [71]	17.4	153 [1.5]	1–3 days	194 [1.9]	4–7 days	182 [1.7]	1–4 weeks	59 [0.6]	> 4 weeks	18 (3.1%)
Tourny et al. [39]				147 (24.3%)	< 7 days	300 (49.5%)	7–28 days	159 (26.3%)	> 28 days	
Emery et al. [72]		20 [2.85]	< 1 day	10 [1.42]	2–7 days	5 [0.71]	8–14 days	4 [0.57]	> 14 days	
Olumide & Ajide [19] ⁱ		10 (83.3%)	0–3 days	2 (16.7%)	4–7 days		8–28 days		> 28 days	
Le Gall et al. [42]	15	357 (31.0%)	1–3 days	337 (29.3%)	4–7 days	344 (29.9%)	1–4 weeks	114 (9.9%)	> 4 weeks	35 (3%)
Ergün et al. [43]	7.24	31 (70.4%)	0–3 days	5 (11.4%)	4–7 days	7 (15.9%)	8–28 days	1 (2.3%)	> 28 days	11 (25%)
Nogueira et al. [44]	18.6	33 (13.3%)	1–3 days	57 (22.9%)	4–7 days	107 (43.1%)	8–28 days	51 (20.6%)	> 28 days	36 (14.5%)
Brito et al. [46] ^d		18 (34%)	1–3 days	6 (11%)	4–7 days	21 (40%)	8–28 days	8 (15%)	> 28 days	
Renshaw & Goodwin [47]				9 (7%)	0–7 days	85 (67%)	8–28 days	33 (26%)	> 28 days	
Nilsson et al. [48]		4 (7%)	1–3 days	13 (21%)	4–7 days	25 (41%)	8–28 days	19 (31%)	> 28 days	
Bult et al. [27]	16.8	201 (32.4%)	1–3 days	116 (18.7%)	4–7 days	208 (33.6%)	8–28 days	95 (15.3%)	> 28 days	
Froholdt et al. [78] ^e		17 (14.8%)	0 days	55 (47.8%)	1–7 days	23 (20%)	8–21 days	20 (17.4%)	> 21 days	
Raya-González et al. [50] ^f	13	5 (13.2%)	1–3 days	7 (18.4%)	4–7 days	21 (55.3%)	8–28 days	5 (13.2%)	> 28 days	
Raya-González et al. [66]		68 (15%)	1–3 days	85 (18%)	4–7 days	225 (48%)	8–28 days	86 (19%)	> 28 days	
Bacon & Mauger [80]				34 (40.0%)	< 7 days	23 (27.06%)	8–14 days	28 (32.94%)	> 15 days	
Jacobs & Van den Berg [53]		276 (50.7%)	Not reported	137 (25.2%)	Not reported	106 (19.5%)	Not reported	25 (4.6%)	Not reported	
Kakavelakis et al. [56]				62 (30%)	< 7 days	79 (38%)	8–28 days	68 (32%)	> 28 days	
Rössler et al. [59] ^h	18.9	119 (28.6%)	0–3 days	84 (20.1%)	4–7 days	115 (27.6%)	8–28 days	99 (23.7%)	> 28 days	
Price et al. [96] ⁱ		315 (80.6%)	0–6 days	26 (6.6%)	7–13 days	13 (3.3%)	14–29 days	35 (8.9%)	> 30 days	
Nagle et al. [92]				316 (42.5%)	< 1 week	226 (30.4%)	1–3 weeks	49 (6.6%)	> 3 weeks	
Female										
Emery et al. [72]		14 [2.02]	< 1 day	14 [2.02]	2–7 days	3 [0.43]	8–14 days	8 [1.15]	> 14 days	
Lislevand et al. [49] ^j		21 (17%)	0–3 days	2 (2%)	4–7 days	0	8–28 days	0	> 28 days	
Froholdt et al. [78] ^e		1 (2.6%)	0 days	17 (44.7%)	1–7 days	13 (34.2%)	8–21 days	7 (18.4%)	> 21 days	
O’Kane et al. [88]		91 (52.9%)	1–7 days	29 (16.9%)	8–14 days	25 (14.5%)	15–21 days	27 (15.7%)	> 21 days	
Schiff [57]		4 (9.1%)	1 day	13 (29.6%)	2–4 days	9 (20.5%)	5–10 days	18 (40.8%)	> 10 days	
Nagle et al. [92]				385 (36.7%)	< 1 week	332 (31.7%)	1–3 weeks	65 (6.2%)	> 3 weeks	
Sokka et al.		44 (56%)	0–3 days	20 (26%)	4–7 days	13 (17%)	8–28 days	1 (1%)	> 28 days	

Note: Percentages (%) were reported in parenthesis and incidence [] per 1000h in square brackets preceded by the absolute number.

TABLE 4. Injury types summary in young soccer players.

References	Age	Maturation	Muscle strain/ contracture	Ligament sprain/rupture	Contusion/ haematoma/ tissue bruising	Fracture/ dislocation	Laceration	Growth- related injuries	Overuse	Tendinosis	Joint injury	Other/ Unknown
Male												
Bianco et al. [67]	U13–U20		93 [1.11]	14 [0.17]								
	U13–U16		63 [1.06]	9 [0.15]								
	U17–U20		30 [1.23]	5 [0.20]								
Bowen et al. [23]	U18–U21		22 [1.9]	35 [3.0]	45 [3.9]	8 [0.7]	2 [0.2]			7 [0.6]	6 [0.5]	8 [0.7]
Deehan et al. [18]			252 (37%)	121 (18%)	71 (10.3%)			23 (3.3%)		41 (5.9%)		
Materne et al. [62]	U9			6 (30%)	7 (35%)	2 (10%)		1 (0.5%)				2 (10%)
	U10			2 (6.9%)	20 (69%)			4 (13.8%)	1 (3.4%)	1 (3.4%)		
	U11			4 (8.3%)	22 (45.8%)	1 (2.1%)		12 (25%)	2 (4.2%)			3 (6.3%)
	U12		1 (2.1%)		23 (48.9%)	2 (4.3%)		12 (25.5%)	2 (4.3%)			
	U13		7 (6.3%)	17 (5.3%)	32 (28.8)	1 (0.9%)		25 (22.5%)	4 (3.6%)	1 (0.9%)		
	U14		12 (6.7%)	14 (7.9%)	38 (21.3%)	10 (5.6%)	2 (1.1%)	44 (24.7%)	11 (6.2%)	1 (0.6%)		3 (1.7%)
	U15		22 (10.3%)	33 (15.4%)	50 (23.4%)	9 (4.2%)	1 (0.5%)	32 (15%)	8 (3.7%)	1 (0.5%)		4 (1.9%)
	U16		22 (8.3%)	42 (15.9%)	77 (29.2%)	1 (0.4%)	1 (0.4%)	35 (13.3%)	16 (6.1%)	1 (0.4%)		2 (0.8%)
	U17		25 (12.3%)	44 (21.6%)	41 (20.1%)	2 (1%)		28 (13.7%)	11 (5.4%)	2 (1%)		5 (2.5%)
	U18		31 (17%)	50 (27.5%)	26 (14.3%)	9 (4.9%)		13 (7.1%)	11 (6.0%)	3 (1.6%)		2 (1.1%)
	U19		6 (24%)	3 (12%)	1 (4%)			2 (8%)	1 (4%)			
Read et al. [36]	U11–U18		162 (20.9%)	136 (17.5%)	57 (7.4%)	25 (3.3%)	18 (2.3%)	51 (6.6%)	33 (4.3%)	33 (4.3%)		209 (27%)
Kemper et al. [69]	U12–U19		18 (13.5%)	22 (16.5%)	29 (21.5%)	3 (2%)		19 (14%)	16 (12%)	6 (4.5%)	9 (7%)	12 (9%)
Frisch et al. [70] ^k	U15–U19		74 (45.4%)	35 (21.5%)	42 (25.8%)	6 (3.7%)				74 (45.4%)		
Le Gall et al. [71] ^l	Early maturers		[0.60]					[0.3]		[0.06]		
	Normal maturers		[0.2]					[0.7]		[0.08]		
	Late maturers		[0.08]					[0.9]		[0.02]		
Cezarino et al. [64]	U11–U20		49 (26.2%)	44 (23.5%)	29 (15.5%)	13 (7.1%)				19 (10.2%)		12 (6.4%)
Timpka et al. [12]	U14–U17		2 (5%)	15 (37%)	12 (29%)	6 (15%)	2 (5%)					2 (5%)
Materne et al. [97]	Mature		30 (7.6%)	66 (16.7%)	122 (30.9%)	5 (1.3%)		25 (6.3%)	23 (5.8%)	8 (2%)	1 (0.3%)	8 (2%)
	Early maturers		31 (4.5%)	96 (13.9%)	230 (33.2%)	12 (1.7%)	2 (0.3%)	83 (12%)	43 (6.2%)	6 (0.9%)	1 (0.1%)	21 (3%)
	Normal maturers		28 (6.3%)	44 (9.9%)	156 (35%)	9 (2%)	2 (0.4%)	84 (18.8%)	16 (3.6%)	4 (0.9%)		7 (1.6%)
	Late maturers		2 (6.3%)	2 (6.3%)	11 (34.4%)	1 (3.1%)		6 (18.8%)	2 (6.3%)	1 (3.1%)		1 (3.1%)
Błażkiewicz et al. [38] ^b	U12–U18		17 (32.7%)	19 (36.5%)		6 (11.5%)	1 (1.9%)				19 (36.6%)	8 (15.4%)
Sullivan et al. [40]	U8–U19		3 (9%)	12 (35%)	13 (38%)	3 (9%)						3 (9%)
Emery et al. [72]	U14–U18		10 [1.42]	10 [1.42]								
Maehlum et al. [41] ⁱ	U14–U18			52 (19.5%)	127 (47.7%)	18 (6.8%)	54 (20.3%)					15 (5.6%)
Olumide & Ajide [19] ^j	U11–U19			3 (17.6%)	2 (11.8%)		11 (64.6%)					1 (6.0%)
Le Gall et al. [42]	U14–U16		176 (15.3%)	192 (16.7%)	352 (30.6%)	78 (6.8%)		72 (6.3%)	19 (1.6%)	108 (9.4%)		52 (4.5%)
	U14		53 (12.6%)	76 (18.1%)	109 (26.0%)	27 (6.5%)		50 (11.9%)	5 (1.2%)	55 (13.1%)		14 (3.3%)
	U15		61 (16.9%)	58 (16.1%)	132 (36.6%)	23 (6.4%)		16 (4.4%)	5 (1.4%)	24 (6.6%)		8 (2.2%)
	U16		62 (16.7%)	58 (15.6%)	111 (29.9%)	28 (7.6%)		6 (1.6%)	9 (2.4%)	29 (7.8%)		30 (8.1%)
Ergün et al. [43]	U17–U19		27 (61.4%)	4 (9.1%)	9 (20.4%)		1 (2.3%)			1 (2.3%)		
	U17		17 (68%)	4 (16%)	2 (8%)		1 (4%)					
	U18		2 (40%)		3 (60%)							
	U19		8 (57.2%)		4 (28.6%)					1 (7.1%)		
Kuzuhara et al. [21]	U10–U12		1 (3.4%)	5 (17.2%)	8 (27.6%)	5 (17.2%)	5 (17.2%)					5 (17.2%)
Brito et al. [22]	U13–U19		61 (31%)	50 (25%)	45 (23%)	11 (6%)				21 (11%)		11 (6%)
	U13		4 (16%)	4 (16%)	8 (32%)	1 (4%)				8 (32%)		
	U15		14 (34%)	7 (17%)	12 (29%)					3 (7%)		5 (12%)
	U17		17 (30%)	13 (23%)	13 (23%)	6 (10%)				5 (9%)		3 (5%)
	U19		26 (34%)	26 (34%)	12 (16%)	4 (5%)				5 (7%)		3 (4%)
Brito et al. [46] ^d	U13–U19		13 (25%)	8 (15%)	13 (25%)	3 (6%)				7 (13%)		
Renshaw & Goodwin [47]	U9–U18		58 (46%)	20 (16%)						16 (13%)		
Nilsson et al. [48]	U15–U19		31 (53%)	15 (24%)								
Bult et al. [27]	U12–U19		173 (27.9%)	78 (12.6%)	174 (28.1%)	56 (9.1%)				81 (13.1%)		
Froholdt et al. [78] ^e	U6–U16		23 (20%)	24 (20.9%)	50 (43.5%)	6 (5.2%)						12 (10.4%)
	U6–U12		7 (16%)	10 (23%)	17 (39%)	3 (7%)						7 (16%)
	U13–U16		16 (23%)	14 (20%)	33 (46%)	3 (4%)						5 (7%)
Khodaei et al. [51]	U14–U18		504 (17.3%)	697 (23.9%)	421 (14.4%)	262 (9.0%)						534 (18.3%)

TABLE 4. Continue.

References	Age	Maturation	Muscle strain/ contracture	Ligament sprain/rupture	Contusion/ haematoma/ tissue bruising	Fracture/ dislocation	Laceration	Growth- related injuries	Overuse	Tendinosis	Joint injury	Other/ Unknown
Herdy <i>et al.</i> [52]	U11–U20		64 (32%)	54 (27%)	62 (31%)						10 (5%)	
	U11		3 (25%)	2 (16%)	7 (59%)							
	U13		6 (39%)	3 (18%)	4 (27%)						1 (6%)	
	U15		17 (37%)	9 (19%)	15 (32%)						2 (4%)	
	U17		24 (37%)	18 (28%)	19 (29%)						3 (4%)	
	U20		14 (22%)	23 (38%)	17 (28%)						4 (7%)	
Hoff & Martin, [79]	U8–U16		28 (23.3%)	46 (38.3%)	22 (18.3%)	8 (6.7%)						16 (13.4%)
Bacon & Mauger, [80]	U18–U21		12 (14.12%)	16 (18.82%)	17 (20%)	5 (5.88%)			16 (18.82%)			7 (8.24%)
McCarroll <i>et al.</i> [54]	U10–U19		17 (9.7%)	47 (26.7%)	44 (25.0%)	22 (12.5%)						41 (23.3%)
Andreassen <i>et al.</i> [55] ^{h, m}	U10–U19		26 (27.1%)	26 (27.1%)	38 (39.6%)	20 (20.8%)						12 (12.5%)
Kakavelakis <i>et al.</i> [56]	U12–U15		49 (23%)	69 (33%)	43 (21%)	16 (8%)				15 (7%)	6 (3%)	7 (3%)
Rössler <i>et al.</i> [59] ^h	U8–U12		70 (16.8%)	86 (20.6%)	94 (22.5%)	44 (13%)	9 (2.1%)	2 (0.5%)	27 (6.5%)	7 (1.7%)		38 (9.1%)
	U8		7 (12.5%)	14 (25.0%)	12 (21.4%)	9 (16.1%)	3 (5.4%)		3 (5.4%)	1 (1.8%)		6 (10.7%)
	U10		11 (9.6%)	25 (21.7%)	27 (23.5%)	15 (13.0%)	2 (1.8%)	2 (1.7%)	9 (7.8%)	2 (1.7%)		13 (11.3%)
	U12		52 (21.1%)	47 (19.1%)	55 (22.4%)	30 (12.2%)	4 (1.6%)		15 (6.1%)	4 (1.6%)		19 (7.7%)
Volpi <i>et al.</i> [60]	U10–U19		7 (9.7%)	23 (31.9%)		16 (22.2%)		22 (30.6%)		4 (5.6%)		
Female												
Emery <i>et al.</i> [72]	U14–U18		9 [1.29]	17 [2.44]								
Maehlum <i>et al.</i> [41] ^j	U14–U18			37 (25.5%)	66 (45.5%)	9 (6.2%)						13 (9.0%)
Del Coso <i>et al.</i> [45]	U18		79 (8.7%)	347 (38.4%)	233 (25.8%)	78 (8.6%)	5 (0.5%)			45 (5%)		
Lislevand <i>et al.</i> [49] ^j	U13–O16		1 (0.8%)	14 (11.7%)	68 (56.7%)		27 (22.5%)		3 (2.5%)			7 (5.8%)
Froholdt <i>et al.</i> [78] ^e	U6–U16		3 (7.9%)	15 (39.5%)	13 (34.2%)	2 (5.3%)						5 (13.1%)
	U6–U12		1 (9%)	3 (27%)	5 (45%)							2 (18%)
	U13–U16		2 (7%)	12 (44%)	8 (30%)	2 (7%)						3 (11%)
Khodaei <i>et al.</i> [51]	U14–U18		488 (15%)	1115 (34.4%)	337 (14.4%)	194 (6.0%)						493 (15.2%)
Watson <i>et al.</i> [81]	U13–U18		3 (11%)	18 (65%)	2 (7%)							
Steffen <i>et al.</i> [86]	U14–U16		77 (23.3%)	141 (42.7%)	78 (23.6%)	9 (2.7%)						24 (7.3%)
O’Kane <i>et al.</i> [88]	U11–U15		108 (62.4%) +	108 (62.4%) +	52 (30%)	7 (4%)						5 (2.9%)
Andreassen <i>et al.</i> [55] ^j	U10–U19		14 (39.9%)	14 (38.9%)	11 (30.6%)	5 (13.9%)						6 (16.7%)
Watson <i>et al.</i> [90]	U16		6 (17%)	22 (61%)	3 (8%)	1 (3%)						

Note: Percentages (%) were reported in parenthesis and incidence [] per 1000h in square brackets preceded by the absolute number.
+ The authors grouped sprain and strain together.

and 30% of injuries, respectively. Twelve studies [27, 36, 39, 42–44, 47, 48, 56, 62, 66, 70] classified severe (major) injuries as those needing more than 28 days to return to play. The injury rate ranged from 2% [43] to 32% [56]. Three studies [23, 71, 72] calculated the incidence, as reported in Table 3. One study [53] did not specify severity classification.

The re-injury condition was also considered in six studies [42–44, 67, 70, 71], which reported a re-injury rate ranging from 3% [42] to 25% [43].

Seven studies [49, 57, 65, 72, 78, 88, 92] reported injury severity in female soccer players but using different criteria of classification. The results, together with severity recorded during tournaments or for traumatic injuries [78], are presented in Table 3.

Injury types

The different types of injury were organised as reported in Table 4.

In male youth soccer players, muscle strains/contractures were recorded, with a percentage ranging between 3% [21] and

61% [43]. Ligament sprains/ruptures involved a number of players ranging from 9% [43] to 38% [79]. Contusions, combined with haematoma and tissues bruising, recorded a percentage prevalence between 7% [36] and 38% [40]. Fractures and dislocations affected young soccer players with a percentage between 2% [69] and 22% [60]. Six studies [12, 21, 36, 38, 43, 59] recorded laceration, as well, with a prevalence from 2% [38] to 17% [21]. Growth related injuries fluctuated from 3% [18] to 31% [60], and tendinosis from 2% [59] to 13% [27]. Only three studies [38, 56, 69] recorded joint injuries.

In young female soccer players, muscle strains and contractures recorded injury prevalence between 9% [45] and 23% [86]. Five studies [45, 51, 81, 86, 90] presented ligament sprains/ruptures; the percentage ranged from 34% [51] to 65% [81]. Contusions combined with haematomas and tissue bruising were in a range between 7% [81] and 26% [45]. Five authors [45, 51, 86, 88, 90] included fractures and dislocations; the value ranged between 3% [86] and 9% [45].

TABLE 5. Injury mechanisms summary in young soccer players.

References	Age	Biological age	Contact injuries	Non-contact injuries	Traumatic/acute	Progressive injury/Overuse	Unknown
Male							
Bowen et al. [23]	U18–U21		59 [5.2]	79 [6.9]			
Deehan et al. [18]	U9–U19		210 (31%)	475 (69%)			
Cloke et al. [37] ^a	U9–U18		24 (42.1%)	32 (57.9%)			
Kemper et al. [69]	U12–U19				88 (65.7%)	46 (34.3%)	
Frisch et al. [70]	U15–U19		60 (36.8%)	95 (58.3%)		8 (4.9%)	
Timpka et al. [12]			30 (68%)	14 (32%)			
Tourny et al. [39]	U12–U15		34 (23%)	114 (77.0%)			
	U16–U20		154 (34.4%)	294 (65.6%)			
Emery et al. [72]	U14–U18		36 (46.15%)	42 (53.85%)			
Olumide & Ajide [19] ^j	U11–U19		14 (93.3%)	1 (6.7%)			
Ergün et al. [43]	U17–U19		14 (60.9%)	9 (39.1%)			
	U17		5 (38.5%)	8 (61.5%)			
	U18		3 (100%)				
	U19		6 (85.7%)	1 (14.3%)			
Kuzuhara et al. [21]	U10–U12		21 (72.4%)	2 (6.9%)			6 (20.7%)
Nogueira et al. [44]	U17–U19		81 (32.8%)	109 (44%)		32 (12.8%)	26 (10.4%)
	U17		47 (19%)	57 (23%)		21 (8.4%)	13 (5.2%)
	U19		34 (13.8%)	52 (21%)		11 (4.4%)	13 (5.2%)
Brito et al. [22]	U13				[0.4]	[0.3]	
	U15				[0.6]	[0.6]	
	U17				[1.0]	[0.7]	
	U19				[1.1]	[0.8]	
Sieland et al. [94]	U12–U19		72 (58%)	53 (42%)			
Renshaw & Goodwin [47]	U9–U18		36 (28%)	91 (72%)			
Materne et al. [97]		Mature	146 (37%)	249 (63%)			
		Early maturers	287 (41.5%)	405 (58.5%)			
		Normal maturers	187 (41.9%)	259 (58.1%)			
		Late maturers	12 (37.5%)	20 (62.5%)			
Bult et al. [27]	U12–U19				468 (75.5%)	152 (24.5%)	
Froholdt et al. [78] ^e	U6–U16		72 (62.6%)	43 (37.4%)			
	U6–U12		28 (64%)	16 (36%)			
	U13–U16		44 (62%)	27 (38%)			
Khodae et al. [51]	U14–U18		1971 (67.7%)	679 (23.3%)		210 (7.2%)	52 (1.8%)
Bacon & Mauger [80]	U18–U21		36 (42.35%)	44 (51.76%)			5 (5.88%)
Kakavelakis et al. [56]	U12–U15		132 (63.4%)	36 (17%)		41 (19.6%)	
Rössler et al. [59] ^h	U8–U12		239 (57.3%)	87 (20.9%)		50 (12.0%)	20 (4.8%)
	U8		33 (59%)	9 (16%)		8 (14.3%)	5 (8.9%)
	U10		74 (64.3%)	19 (16.5%)		16 (13.9%)	4 (3.5%)
	U12		132 (53.7%)	59 (23.9%)		26 (10.6%)	11 (4.5%)
Volpi et al. [60]	U10–U19		26 (36.2%)	46 (63.8%)	47 (65.2%)	25 (34.8%)	
Female							
Soligard et al. [24]	U16		133 (51%)	115 (44%)	203 (78%)	56 (22%)	11 (5%)
Del Coso et al. [45]	U18		195 (21.6%)	709 (78.4%)			
Schiff et al. [58]	U12–U14				27 (4.7)	17 (2.9)	
Lislevand et al. [49] ⁱ	U13–O16		106 (94%)	7 (6%)			
	U13		43 (96%)	2 (4%)			
	U16		40 (93%)	3 (7%)			
	O16		23 (92%)	2 (8%)			
Froholdt et al. [78] ^e	U6–U16		23 (60.5%)	15 (39.5%)			
	U6–U12		7 (64%)	4 (36%)			
	U13–U16		16 (59%)	11 (41%)			
Khodae et al. [51]	U14–U18		2249 (69.4%)	700 (21.6%)		226 (7.0%)	67 (2.1%)
Steffen et al. [86]	U14–U16				330 (86.8%)	50 (13.2%)	
Clausen et al. [87] ^g	U15–U18		16 (47%)	7 (20.5%)	23 (67.6%)	11 (32.3%)	
O’Kane et al. [88]	U11–U15		115 (66.5%)	58 (33.5%)			

Note: Percentages (%) were reported in parenthesis and incidence [] per 1000h in square brackets preceded by the absolute number.

TABLE 6. Anatomic location summary of injuries in young soccer players

References	Age	Lower extremities	Ankle and foot	Lower leg/ Calf/Achilles tendon	Knee	Posterior thigh	Anterior thigh	Thigh	Groin/ adductors/ pelvis/hips	Upper body/ Abdomen/ lower back/ trunk	Arm/ shoulder/ hand/wrist	Other
Male												
Elias [35] ⁱ	U12–U19		598 (25.4%)	216 (9.2%)	348 (14.8%)			304 (12.9%)		194 (8.2%)	60 (2.5%)	
	U12		72 (24.2%)	25 (8.4%)	57 (19.1%)			32 (10.7%)		22 (7.4%)	5 (1.7%)	
	U14		155 (25.6%)	58 (9.6%)	76 (12.5%)			77 (12.7%)		66 (10.9%)	9 (1.5%)	
	U16		190 (24.1%)	70 (8.9%)	118 (15.0%)			117 (14.8%)		65 (8.2%)	26 (3.3%)	
Wik et al. [61]	U13–U18		247 (22%)	100 (9%)	145 (13%)			274 (25%)	159 (14%)	62 (6%)	97 (9%)	
	U19		181 (29.0%)	63 (10.1%)	97 (15.5%)			78 (12.5%)		41 (6.6%)	20 (3.2%)	
Bianco et al. [67]	U13–U20			12 [0.14]	19 [0.22]			36 [0.43]	23 [0.27]			
	U13–U16			7 [0.12]	12 [0.20]			23 [0.38]	18 [0.30]			
	U17–U20			5 [0.20]	7 [0.28]			13 [0.53]	5 [0.20]			
Bowen et al. [23]	U18–U21		54 [4.7]	4 [0.4]	19 [1.7]	10 [0.9]	11 [1.0]		18 [1.6]	4 [0.4]	8 [0.7]	
Deehan et al. [18]	U9–U19		165 (24%)		102 (15%)			211 (31%)	44 (6.5%)	69 (10%)		94 (13.5%)
Cezarino et al. [64]	U11–U20		42 (22.5%)	8 (4.2%)	43 (23%)			48 (25.7%)	22 (11.8%)	7 (3.7%)	2 (1%)	
Read et al. [36]	U11–U18		206 (25.7%)	17 (2.1%)	161 (20.0%)	49 (6.1%)	76 (9.5%)		113 (14.1%)	48 (6.0%)	51 (6.3%)	11 (1.4%)
Frisch et al. [70]	U15–U19		38 (23.3%)	5 (3.1%)	28 (17.2%)			63 (38.7%)	8 (4.3%)	9 (5.5%)	7 (4.2%)	
Timpka et al. [12]	U14–U17	25 (58%)	13 (32%)	2 (5%)	4 (10%)	1 (2%)	2 (5%)		5 (7%)	4 (10%)	5 (12%)	
Błażkiewicz et al. [38] ^b	U12–U18	29 (55.8%)								9 (17.3%)	18 (34.6%)	
Tourny et al. [39]	U12–U15	130 (87.7%)	17 (10.4%)		24 (14.7%)			38 (23.3%)	31 (19.0%)	12 (7.4%)	4 (2.5%)	
	U16–U20	415 (92.6%)	81 (26.6%)	27 (6.0%)	53 (11.8%)			144 (32.1%)	72 (16.1%)	12 (2.7%)	18 (4.0%)	
Emery et al. [72]	U14–U18		11 (1.56)	5 (0.71)	4 (0.57)			2 (0.28)	3 (0.43)	2 (0.28)		
Maehlum et al. [41] ⁱ	U14–U18	159 (59.8%)								16 (6.0%)	37 (13.9%)	
De Ridder et al. [74]	U11–U17		12 (18%)	6 (9%)		4 (6%)	12 (18%)		13 (19%)			
Olumide & Ajide [19] ⁱ	U11–U19		1 (6.0%)		3 (17.6%)			3 (17.6%)	3 (17.6%)		6 (35.2%)	
Le Gall et al. [42]	U14–U16		300 (26%)	60 (5.2%)	176 (15.3%)			282 (24.5%)	82 (7.1%)	113 (9.8%)	119 (10.3%)	
	U14		116 (27.6%)	24 (5.7%)	74 (17.6%)			89 (21.2%)	33 (7.9%)	31 (7.4%)	48 (11.5%)	
	U15		82 (22.7%)	19 (5.3%)	49 (13.6%)			107 (29.6%)	24 (6.7%)	36 (10.0%)	35 (9.7%)	
	U16		102 (27.5%)	17 (4.6%)	53 (14.3%)			86 (23.2%)	25 (6.8%)	46 (12.4%)	36 (9.8%)	
Materne et al. [62]	U9		10 (50%)	3 (15%)	4 (20%)						3 (15%)	
	U10		9 (31%)	4 (13.7%)	9 (31%)			4 (13.7%)			3 (10.3%)	
	U11		22 (45.8%)	5 (10.5%)	9 (18.8%)			5 (10.5%)	3 (6.3%)	1 (2.1%)	3 (6.3%)	
	U12		10 (21.3%)	10 (21.2%)	6 (12.8%)			9 (19.1%)	4 (8.5%)	3 (6.4%)	5 (10.6%)	
	U13		25 (22.5%)	20 (18%)	16 (14.4%)			23 (19.8%)	7 (6.3%)	6 (5.4%)	13 (11.7%)	
	U14		32 (19.6%)	30 (16.8%)	15 (8.4%)			46 (25.8%)	29 (16.3%)	9 (5.1%)	8 (4.5%)	
	U15		52 (24.3%)	25 (11.6%)	16 (7.5%)			51 (23.8%)	32 (15%)	18 (8.4%)	9 (4.2%)	
	U16		70 (26.5%)	31 (11.8%)	34 (12.9%)			64 (23.1%)	37 (14%)	17 (6.5%)	5 (1.9%)	
	U17		53 (26%)	11 (5.4%)	26 (12.7%)			59 (27.5%)	37 (18.1%)	6 (3%)	6 (3%)	
	U18		43 (26.6%)	12 (6.6%)	31 (17%)			59 (32.4%)	18 (9.9%)	7 (3.8%)	8 (4.4%)	
Schmidt-Olsen et al. [20]	U13–U17		73 (23.4%)	34 (10.9%)	81 (26%)				28 (8.9%)	43 (13.8%)	32 (10.3%)	
	U13		30 (21.8%)	12 (8.8%)	39 (28.5%)				15 (11%)	18 (13.1%)	12 (8.8%)	
	U15		13 (19.4%)	10 (15.0%)	17 (25.3%)				3 (4.5%)	13 (19.4%)	8 (11.9%)	
	U17		30 (27.7%)	12 (11.1%)	25 (23.1%)				12 (11.1%)	12 (11.1%)	11 (11%)	
Ergün et al. [43]	U17–U19		5 (11.4%)	2 (4.6%)	3 (6.8%)			14 (31.8%)	11 (25%)	6 (13.6%)		
	U17		2 (8%)	2 (8%)	2 (8%)			8 (32%)	8 (32%)	1 (4%)		
	U18		2 (40%)							3 (60%)		
	U19		1 (7.1%)		1 (7.1%)			6 (42.9%)	3 (21.5%)	2 (14.3%)		
Kuzuhara et al. [21]	U10–U12	15 (51.7%)								2 (6.9%)	4 (13.8%)	3 (10.3%)
Nogueira et al. [44]	U17–U19		64 (25.8%)	18 (7.3%)	34 (13.7%)	31 (12.5%)	30 (12.1%)	61 (24.6%)	35 (14.1%)	22 (8.9%)	13 (5.2%)	
Brito et al. [22]	U13–U19	172 (86%)	61 (31%)	14 (7%)	24 (12%)			60 (30%)	14 (7%)	8 (5%)	14 (7%)	
	U13		10 (39%)	2 (8%)	3 (13%)			6 (25%)	2 (8%)	1 (4%)	1 (4%)	
	U15		7 (17%)	3 (7%)	4 (10%)			14 (34%)	4 (10%)	6 (15%)	2 (5%)	
	U17		13 (23%)	7 (12%)	9 (16%)			15 (26%)	5 (9%)	1 (2%)	6 (11%)	
	U19		31 (40%)	2 (3%)	8 (11%)			25 (33%)	3 (4%)		5 (6%)	
Brito et al. [46] ^d	U13–U19		16 (30%)	5 (9%)	5 (9%)			12 (23%)	4 (8%)	6 (11%)	3 (6%)	
Renshaw & Goodwin [47]	U9–U18		22 (17.3%)	7 (5.5%)	22 (17.3%)	17 (13.4%)	27 (21.6%)		17 (13.4%)	6 (4.7%)	6 (4.7%)	
Nilsson et al. [48]	U15–U19		12 (19.7%)	4 (6.6%)	5 (8.2%)			16 (26.2%)	20 (32.8%)	1 (1.6%)	3 (4.9%)	
Bult et al. [27]	U12–U19											

TABLE 6. Continue.

References	Age	Lower extremities	Ankle and foot	Lower leg/ Calf/Achilles tendon	Knee	Posterior thigh	Anterior thigh	Thigh	Groin/ adductors /pelvis/hips	Upper body/ Abdomen/ lower back/ trunk	Arm/ shoulder/ hand/wrist	Other
Froholdt et al. [78] ^e	U6–U16		35 (30.4%)	13 (11.3%)	12 (10.4%)			18 (15.63%)	12 (10.4%)	9 (7.8%)		
	U6–U12		17 (38%)	5 (11%)	7 (16%)			4 (9%)	2 (5%)	2 (5%)		
	U13–U16		18 (25%)	8 (11%)	5 (7%)			14 (20%)	10 (14%)	7 (10%)		
Khodae et al. [51]	U14–U18		723 (24.8%)	229 (7.9%)	409 (14.1%)			363 (12.5%)	148 (5.1%)	140 (4.8%)	286 (9.8%)	24 (0.8%)
Hoff & Martin [79]	U8–U16	72 (60%)								15 (12.5%)	17 (14%)	
Bacon & Mauger [80]	U18–U21		32 (37.65%)	2 (2.35%)	14 (16.47%)	3 (3.53%)	6 (7.06%)		15 (17.65%)	6 (7.06%)	2 (2.35%)	2 (2.35%)
Jacobs & Van den Berg [53]			145 (26.6%)	12 (2.2%)	52 (9.5%)				77 (14.1%)	9 (1.6%)	128 (23.5%)	
McCarroll et al. [54]	U10–U19		44 (25%)	44 (25%)	25 (14.2%)	2 (1.1%)	21 (11.9%)		5 (2.8%)	2 (1.1%)	13 (7.4%)	
Andreasen et al. [55] ^j	U10–U19	71 (73.9%)								3 (3.1%)	13 (13.5%)	
Kakavelakis et al. [56]	U12–U15		60 (29%)	13 (6%)	75 (36%)			19 (9%)		11 (5%)	25 (12%)	
Rössler et al. [59] ^h	U8–U12		139 (33.4%)	29 (7.0%)	68 (16.3%)			41 (9.8%)	41 (9.8%)	8 (2%)	65 (15.6%)	
	U8		26 (46.4%)	2 (3.6%)	6 (10.7%)			4 (7.1%)	5 (8.9%)		8 (14.3%)	
	U10		44 (38.2%)	10 (8.7%)	19 (16.5%)			7 (6.1%)	8 (7.0%)	2 (1.8%)	14 (12.2%)	
	U12		69 (28.1%)	17 (6.9%)	43 (17.5%)			30 (12.2%)	28 (11.4%)	6 (2.4%)	43 (17.5%)	
Price et al. [96] ⁱ	U5–U18		15 (3.8%)	59 (15.1%)	75 (19.1%)			17 (4.3%)	77 (19.6%)	42 (10.7%)	76 (19.4%)	
Volpi et al. [60]	U10–U19		15 (20.8%)	2 (2.8%)	30 (41.7%)			7 (9.7%)	8 (11.1%)		9 (12.5%)	
Nagle et al. [92]	U14–U18		(35.4%)		(26.3%)			(23.1%)				
Female												
Elias [35] ^j	U12–U19		394 (28.4)	104 (7.5%)	271 (19.5%)			106 (7.6%)		196 (14.1%)	24 (1.7%)	
	U12		46 (24.1%)	12 (6.3%)	43 (22.5%)			12 (6.3%)		14 (7.3%)	4 (2.1%)	
	U14		113 (25.7%)	27 (6.1%)	82 (18.7%)			33 (7.5%)		41 (9.3%)	11 (2.5%)	
	U16		162 (31.7%)	37 (7.2%)	96 (18.8%)			38 (7.4%)		35 (6.8%)	6 (1.2%)	
	U19		73 (29.7%)	28 (11.4%)	50 (20.3%)			23 (9.3%)		16 (6.5%)	3 (1.2%)	
Emery et al. [72]	U14–U18		17 [2.44]	1 [0.14]	11 [1.58]			3 [0.43]	5 [0.72]	1 [0.14]	3 [0.43]	
Maehlum et al. [41] ^j	U14–U18			159 (59.8%)						15 (10.3%)	21 (14.4%)	
Del Coso et al. [45]	U18		241 (26.6%)	77 (8.5%)	270 (29.9%)			73 (8.1%)	18 (2%)	45 (5%)	131 (14.5%)	
Lislevand et al. [49] ^j	U13–U16		44 (36.7%)	9 (7.5%)	30 (25%)			9 (7.5%)	6 (5%)	3 (2.5%)	18 (15%)	
Froholdt et al. [78] ^e	U6–U16		13 (34.2%)	1 (2.6%)	8 (6.9%)			3 (7.9%)	1 (2.6%)	3 (7.9%)		
	U6–U12		2 (18%)	1 (9%)	3 (27%)				1 (9%)	1 (9%)		
	U13–U16		11 (41%)		5 (19%)			3 (11%)		2 (7%)		
Khodae et al. [51]	U14–U18		880 (27.2%)	222 (6.9%)	637 (19.7%)			339 (10.5%)	93 (2.9%)	97 (3.0%)	218 (6.8%)	19 (0.6%)
Watson et al. [81]	U13–U18		13 (47%)		5 (18%)			3 (11%)		2 (7%)		
O’Kane et al. [82] ⁱ	U12–U15		16 (19.8%)	7 (8.6%)	38 (46.9%)			4 (4.9%)	16 (19.8%)			
Steffen et al. [86]	U14–U16		147 (44.6%)	17 (5.2%)	53 (16.1%)			49 (14.8%)	23 (7%)	27 (8.2%)		
O’Kane et al. [88]	U11–U15		84 (48.5%)	9 (5.2%)	43 (24.9%)			19 (11%)	18 (10.4%)			
Andreasen et al. [55] ^j	U10–U19	23 (63.9%)								4 (11.1%)	6 (16.7%)	
Schiff [57]	U11–U14	35 (77.5%)								4 (8.9%)	6 (13.3%)	
Watson et al. [90]	U16		17 (47%)	1 (3%)	7 (19%)					2 (6%)	4 (11%)	
Nagle et al. [92]	U14–U18		(37.7%)		(33.4%)			(17.2%)				

Note: Percentages (%) were reported in parenthesis and incidence [] per 1000h in square brackets preceded by the absolute number^a The authors report only ankle injuries.

^a The authors report only ankle injuries; ^b The authors report only goalkeeper injuries; ^c Data refer only to non-contact injuries; ^d The authors report only preseason injuries; ^e Data refer to traumatic injuries; ^f The authors report only muscle injuries; ^g Data refer to knee injuries; ^h Data refer to a mixed sample, male and female; ⁱ The authors report only overuse injuries; ^j Data were recorded during tournament; ^k The authors combine muscle and tendon injuries; ^l Data refer to groin strain; ^m The authors combine sprain and strain.

Studies reporting injury incidence [23, 67, 72], and data recorded according to chronological age [22, 42, 43, 52, 59, 67, 78], biological age [71, 97] or specific cases such as data collected during tournament [19, 36, 41, 49] are presented in Table 4.

Injury mechanisms

Considering the injury mechanism, fifteen studies [12, 18, 21, 23, 39, 43, 44, 47, 51, 56, 60, 70, 72, 80, 94] reported comparison between contact and non-contact injuries in male youth soccer players. The percentage ranged from 23% [39] to 72% [21] for contact injuries and from 7% [21] to 77% [39] for non-contact injuries. Three studies [27, 60, 69] made a distinction between traumatic and overuse injury, reporting a percentage ranging from 65% [60] to 76% [27] for traumatic injuries and from 25% [27] to 35% [60] for overuse injuries. Four studies [44, 51, 56, 70] showed only overuse/progressive injuries and the percentage ranged from 5% [70] to 20% [56]. Four studies [24, 45, 51, 88] made a comparison between contact and non-contact injuries in female youth soccer players. The range was from 22% [45] to 69% [51] for contact injuries and from 22% [51] to 78% [45] for non-contact injuries. Two authors [24, 86] investigated traumatic and overuse injuries, as well. The percentage values were 78% and 87%, respectively, for traumatic injuries, and 22% and 13%, respectively, for overuse injuries.

Injury mechanism data are presented in Table 5 according to chronological age, biological age, and for specific cases such as tournament injuries [19, 49] or specific anatomical areas [37, 87].

Anatomical location

The anatomical districts of injuries were organised as reported in Table 6. When the articles presented data for individual anatomical areas, they were grouped by the authors reporting the overall percentage. Head, neck, and cervical spine injuries were not reported.

In general, in male youth soccer players, five studies [21–23, 41, 79] reported an overall prevalence of lower extremity injuries. They were the most common anatomical injured district with a percentage ranging between 52% [21] and 93% [39]. In particular, ankle and foot in conjunction registered a prevalence ranging between 10% [39] to 38% [80]. Several studies recorded lower leg (calf/ Achilles tendon) injuries. The percentage ranged between 2% [36] and 25% [54]. The knee registered a range between 7% [43] and 42% [60]. Twelve studies [18, 39, 42–44, 48, 51, 56, 60, 67, 70, 92] reported the overall percentage of injuries in the thigh. The range was from 9% [56] to 39% [70]. Specifically, the prevalence ranged from 5% [12] to 22% [47] for the anterior thigh and from 1% [54] to 13% [47] for the posterior thigh.

Hip injuries, including groin, adductors, and pelvis injuries, recorded a percentage ranging between 3% [54] and 33% [48]. For the upper body, the range was from 1% [54] to 14% [20]. The upper extremities, including the arm, shoulder, wrist, hand, and fingers, recorded a range from a minimum of 2% [80] to a maximum of 23% [53].

In women's youth soccer, the ankle and foot were affected with a percentage ranging between 27% [45] and 49% [88]. The injury

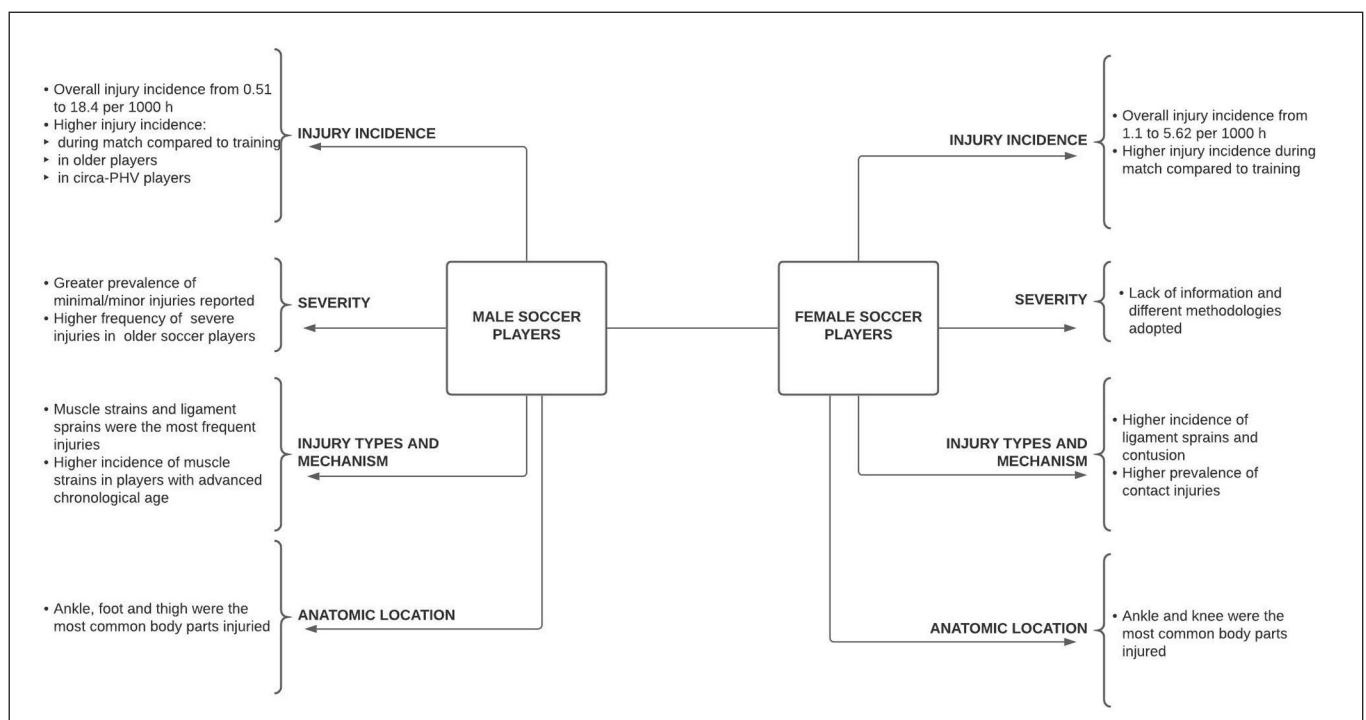


FIG. 2. Summary of the main results.

incidence recorded was 2.44 [72]. Six studies [45, 51, 57, 81, 86, 88] reported injury prevalence in the lower leg with a percentage ranging from 3% [90] to 9% [45]. For the knee, the value ranged from 16% [86] to 33% [92]. Six studies [45, 51, 81, 86, 88, 92] identified thigh injuries with a range from 8% [45] to 17%. Four studies [45, 51, 86, 88] recorded injuries in the hip area with a percentage from 2% [45] to 20% [88] and an injury incidence of 0.72 [72]. For the upper body, the range was from 3% [51] to 9% [57], while for upper extremities it was from 7% [51] to 15% [45].

Injury prevalence according to chronological age and for specific cases such as goalkeeper injuries [38], only traumatic injuries [78], and preseason injuries [46], is presented in Table 6.

DISCUSSION

Although soccer is generally considered a safe sport, much attention has been placed during the last years on injury risk in young soccer players. The need to reduce medical health care costs and to promote talent development prompted investigation of the injury rate and risk factors related to it. Following the suggestion of Van Mechelen et al. [17], before introducing adequate prevention strategies, it is necessary to describe sports injuries and to identify the mechanism underlying them.

Therefore, the aim of this systematic literature review was to summarise and to show a broad view of injury incidence and injury risk factors in young soccer players regardless of different injury definitions or different sample characteristics such as chronological age, biological age, sex, or level of play. According to the authors' best knowledge, this is the first review that tries to build a general overview of the risk of injury in young soccer players combining epidemiological data and injury risk factors together. The main results are summarised in Figure 2.

Injury definition and collection process

The absence of standardization in the research method produces confusion and difficulty in the interpretation of the results [99, 101]. In order to avoid this bias, Fuller et al. [98], introduced the consensus statement on injury definitions and data collection procedures. However, even after the publication of the consensus statement, many studies continued to use different definitions [21, 50, 74, 77]. This helps to explain the high variability of the results found in the current review. In general, the two main strategies adopted to detect injury condition were time loss [18, 36, 42, 61, 73] and medical attention required [7, 12, 20, 72]. The latter method allows attention to be paid to a higher number of injuries, with the risk of overestimating or including injuries not clinically relevant. The time-loss method, on the other hand, is mainly based on days of absence, but also in this case, the use of different time windows, from 24 h [51, 56] up to four weeks [96], increases the variability of results.

The collection process strategies were closely connected with the experimental design. Even in this case, the adoption of different data collection methods could produce discrepancy in results [102, 103].

Physiotherapists, physicians and medical staff have been widely recruited for prospective cohort studies [18, 23, 48, 68, 75]; however, few studies [51, 53, 56, 57, 79, 83, 85, 90] adopted questionnaires or web data collection tools. Schiff et al. [58] found high agreement between certified athletic trainers and an Internet-based survey about the injury collection process. Support from parents in reporting injuries could be a valid alternative to the medical staff, especially in clubs with limited economic resources; in spite of this, the possibility of subjective answers and the inability to discriminate different kinds of injuries remain to be considered.

In retrospective studies [38, 53, 57, 79], self-administered questionnaires were mainly used. This method allows one to collect injury data quickly without requiring all the time necessary for prospective studies. In this case, there are some limits connected with recall bias [103, 104] and inability to report incidence or severity [105]. Therefore, authors should be aware that the choice of injury definition and data collection method could impact the quality of the epidemiological analysis [103].

Injury incidence and severity

The overall injury incidence per 1000 h ranged from 0.51 [40] to 18.4 [43] in male youth soccer players, with an average number of injuries between 0.6 [18] and 2.5 [71] per player. The high variability, as previously mentioned, could be explained by the different injury definitions, collection processes, and sample characteristics. Although the absolute number of injuries recorded during matches and training was similar [18, 21] or sometimes higher during training [48, 53], the injury incidence was considerably higher during matches [21, 23, 42, 69]. The competition subjects players to greater physiological and psychological demands, unlike training, during which the aim is to improve performance and to reduce the risk of injury [39]. This is better shown during youth soccer tournaments, where the authors found injury incidence up to 113.6 per 1000 h [19]. Tournaments are generally played in few days, and every match is crucial to reach the final stage. The high density of matches, with a short recovery time in between, and the technical and tactical demands, further contribute to increase the risk of injury. As evidence of this, Maehlum et al. [41] reported an injury rate that increased during the final rounds, played in knockout, compared to opening rounds.

Another factor that explains the variability of the results is the different players' chronological age considered in the studies. Soccer players aged from 5 to 18 years old were included in the analysis. It is well known that this age group encompasses different development stages passing from childhood to adolescence. In this period of their life, athletes experience rapid changes – psychological, physiological, cognitive, and behavioural – accompanied by an increase in weight, height, muscle mass and changes in body composition [106]. This anthropometric growth, together with hormonal and motor control changes, may produce different injury predispositions in young soccer players [73]. Many studies [20, 36, 42, 61, 76, 78] reported an

increase in injury rate with chronological age. As the years passed, players become faster and stronger [78] and they are subjected to higher volume of exposures and intensity of competition than in the past, and all these factors may contribute to increased injury incidence. However, if it is true that the overall injury incidence increases with age, it seems that training injury incidence was higher in younger soccer players [42, 43, 64], who, lacking technical and tactical skills, may be more susceptible to a higher risk of injury [42, 43]. However, not all the studies reported significative differences according to chronological age [44, 67].

As mentioned before, adolescence is a period characterised by rapid psychological and physiological changes; therefore, players with the same chronological age could experience different stages of puberty. For this reason, a few studies tried to investigate how biological age impacts on the injury rate. In this regard, three studies [71, 77, 97] adopted X-ray assessment to identify early, normal, and late maturer players. Materne et al. [97] found the greatest overall injury risk in early maturer players. Le Gall et al. [71] did not find a significant difference in overall injury incidence, but observed that early and late maturers may be vulnerable to different types of injuries. Johnson et al. [77] found more injuries in early maturers than in late or normal maturers, but the analysis did not reveal differences after adjusting for training time, playing time, height, and position played. Further analysis is needed to clarify whether early or late maturation may impact on injury predisposition. However, greater agreement was found in studies [27, 73, 89] adopting the maturity offset method to assess maturity timing [107]. Particularly, a higher injury incidence was found in the period labelled as circa-PHV, which is the period characterised by a rapid growth spurt. In this particular period known as “adolescent awkwardness”, the motor control strategies are altered [108], and the rapid growth of anatomical structures such as tendons, ligaments and bones may predispose soccer players to a higher risk of injury. Only one study adopted the Khamis Roche equation to assess the status of maturation of the players [63]. The authors observed increased injuries in players classified as “early-maturing” compared to “on-time” or “late-maturing” players.

Chronological and biological ages also appear to affect the severity of injuries. The different time intervals used to classify minimal, minor, moderate, and severe injuries make the comparison between the reported studies difficult. However, most studies found a greater prevalence of minimal/minor injuries [39, 42, 43, 51, 53, 56, 62, 70, 71, 78] with a mean recovery time requiring less than one week. A few studies [12, 44] recorded a high prevalence of severe injuries. Moreover, severe injuries may be more frequent in older players [22, 39, 67]. This result is in line with previous studies conducted on adult soccer players [109, 110]. The re-injury rate reported was low, almost always close to 3% [22, 42, 44, 67, 71], and in a few cases higher than 15% [43, 70]. The re-injury rate may be affected by the presence or absence of a team’s medical staff, and by imposed pressures to return to play, particularly in elite and

older categories. Furthermore, only four studies [27, 61, 62, 66] reported injury burden, which is the result of combination of severity and incidence. The highest injury burden was found in U16 [27, 61, 66] and U18 soccer players [62]. This may be explained by the rapid changes in height and weight that characterise these age groups, as well as by the increase in the training and match demands [61]. Despite being poorly adopted in youth soccer studies, this parameter has been widely used in rugby epidemiological studies [111–113], proving to be very useful to quantify the overall impact of an injury [103].

Of the total amount of articles, only nineteen reported injury incidence rates in female soccer players. The overall injury incidence ranged between 1.1 [40] and 7.20 [65], and also in this case the rate was higher during matches than during training [51, 57, 65, 92]. The overall range found was very similar compared to injury incidence in male players. In fact, several studies which investigated injury rates in young male and female soccer players [72, 78, 83] did not find significant differences, although other studies [51, 55, 76] reported a higher injury rate in the female sample. While it is well recognised that female athletes are more prone to ACL injury [114], due to hormonal, anthropometric and biomechanical factors, it is not yet clear whether sex difference may affect predisposition to other kinds of injury. Only a few studies [49, 57, 72, 78, 88, 92] reported injury severity in young female soccer players, and the use of different methods of classification makes any comparison difficult.

Injury incidence according to participant level

The overall injury incidence identified in elite and non-elite male young soccer players was very similar. By contrast, the training injury rate observed was slightly higher in elite players. However, substantial differences were found comparing match injury rate. The range was from 2.84 [67] to 47.7 [43] in elite young soccer players, and from 1.8 [92] to 24.67 [65] in non-elite young soccer players. Although differences in injury risk between elite and non-elite groups have been investigated in adult soccer players [115], there is a lack of information in young soccer players. The higher injury rate found during training and, in particular, during matches may be explained by the higher play intensity that increases with the competitive level.

In female young soccer players, however, it is not possible to make any comparisons due to the scarcity of information in elite groups.

Injury types and mechanism

Understanding the mechanisms underlying soccer-related injuries allows effective prevention strategies to be developed [116]. The most common types of injury reported in young male soccer players were muscle strains and ligament sprains [25, 36, 38, 43, 46, 64, 66, 67, 70, 89]. Other studies reported a higher prevalence of contusions/haematoma [42, 52, 69], which are more predominant during matches [21] or tournaments [41, 55], explained by the high intensity and speed required during these events. Fractures, lacerations and tendinosis appear to be less frequent in young soccer

players [36, 42, 43, 56, 69, 79]. However, injury types may present different distribution and variability according to chronological and biological age. A higher proportion of muscle strains was observed in older players [22, 42, 62, 78] compared to younger ones. The increase in training load and competitiveness combined with incomplete muscle mass development may predispose athletes to muscle strains [96] and explain this finding. In addition, when injury types were analysed according to skeletal age, strains were more common in early maturer players [71]. In contrast, osteochondrosis disorders such as Osgood-Schlatter's disease were mostly found in younger players, in particular at the beginning and at the end of their growth spurt [96]. In fact, the growth spurt phase represents a critical moment for young athletes, when bone and soft tissue development could lead to a reduction in flexibility and in turn to growth-related injuries. Contrarily, young female soccer players appear to be more prone to ligament sprains than muscle strains [41, 45, 49, 51, 72]. In this regard, Del Coso et al. [45] speculated that hormonal release during the different menstrual phases (i.e. progesterone, oestrogen) may affect ligament laxity and neuromuscular control. In support of this hypothesis, O'Kane et al. [117] reported a higher risk of injury in postmenarchal players. Contusions also had high prevalence in young female soccer players [41, 49, 78, 86], while fractures, lacerations, and growth-related injuries had a low impact [41, 45, 49, 86].

Less agreement was found regarding the mechanism of injuries in male youth players. Several studies recorded a higher rate of contact injuries [12, 21, 43, 51, 56, 70, 78], but at the same time many others reported a higher prevalence of non-contact injuries [18, 37, 39, 44, 47, 60, 70]. These results highlight the need to act bidirectionally in order to promote prevention strategies and reduce the risk of injury: first, developing good habits [78] and improving adherence to a fair-play policy in order to reduce violent behaviour linked to contact-related injuries [118]; on the other hand, trying to avoid non-contact injuries through monitoring the weekly training load [23], improving neuromuscular control [119], and promoting intervention strategies such as adoption of the "11+ Kids" programme [120].

In contrast, in female soccer, almost all the studies [24, 49, 51, 78, 87, 88] reported a strong prevalence of contact injuries, with the percentage ranging from 47% to 94%. This discrepancy with male soccer is not very clear. However, it is possible to speculate that different technical and tactical skills, as well as the adoption of different rules, may affect the results and the differences between the sexes.

Anatomical location

Lower extremities were the most common injured body region in both male and female soccer players. However, it is possible to observe different anatomical distributions according to sex. In male soccer players the ankle and foot [12, 20, 23, 36, 42, 51, 65, 80, 96] together with the thigh [18, 39, 43, 48, 64, 67, 70] were the most common body parts injured. When reported, the anterior thigh showed higher prevalence compared to the posterior

thigh [12, 36, 47, 54, 74, 80]. Regarding ankle injuries, the injury rate seems to increase with players' age [20, 22, 35, 42]. One study [37], which focused exclusively on ankle injuries, confirmed this trend. According to previous studies [18, 20, 60], increasing volume exposure in training and matches, as well as increasing speed and muscle mass, may explain this tendency.

Furthermore, other studies recorded a high prevalence of groin injuries [39, 43, 48, 74, 80, 96]. In particular, one study found a higher rate of groin injuries in early maturer players [71], who, presenting an advanced biological age, were more predisposed to this kind of injury, as reported in a previous systematic review [121]. On the other hand, upper body and upper extremities showed a lower prevalence [12, 18, 36, 39, 41, 44, 47, 80] except for one study [38] conducted on goalkeepers, who, for reasons connected with playing position, are more exposed to elbow, forearm, wrist, and hand injuries. However, upper limb injuries might not be considered relevant to soccer participation, and therefore this could lead to their underestimation in epidemiological analysis [102].

In young female soccer players, the ankle and foot registered a high injury rate [35, 45, 49, 65, 72, 78, 85] as in male players, but they presented more knee injuries [41, 45, 49, 72, 88, 90]. As previously mentioned, this discrepancy could be explained by different sex characteristics: anatomical (Q angle), neuromuscular (hamstrings/quadriceps ratio), and hormonal (i.e. oestrogen, progesterone and relaxin) [122].

In female, as in male, young soccer players, upper body and upper extremities presented low prevalence [41, 45, 78, 90].

LIMITATIONS OF THIS REVIEW

This review presents several strengths; to the best of our knowledge, this is the first review that combines epidemiological data and injury risk factors. Moreover, unlike previous reviews on young soccer players, female players were included in the analysis.

However, several limitations must be considered. The heterogeneity of the studies, mainly due to the different injury definitions used, did not allow us to perform statistical or meta-analysis of the results. Furthermore, the follow-up period was highly variable, ranging from a few days during tournaments [93] to 10 seasons [42, 71].

Moreover, studies reporting injuries in retrospective design were included. In this case, recall bias may underestimate the real number of injuries.

Several factors contributed to make comparison between articles difficult: some articles reported injury prevalence without injury incidence [18, 47], many authors reported injuries collected with different age ranges, the severity of injuries relied on contrasting classification methods [19, 23, 96] and, regarding anatomical location, many studies used different strategies to group the various anatomical districts.

Including articles regardless of playing level allows one to increase the amount of data to analyse; however, different technical levels, coaching style, and age of specialisation may affect injury incidence.

CONCLUSIONS

Although soccer is generally considered a safe sport, injuries in young soccer players may have serious consequences: dropout, sequelae, and economic impact. The interest in the analysis of injuries in youth soccer has increased exponentially in the last years. The introduction of international consensus statements [98, 103] made it possible to increase the quality of the studies (injury definition, severity definition, types of injuries recorded). Moreover, there has been an increase in the number of players involved and in the length of studies. In addition, a comparison between the recent studies (last 2–3 years) with the past studies shows the increased use of parameters such as injury burden [61, 62] that allow better quantification of the injury impact in young soccer players.

Our analysis showed a different predisposition to injury according to sex, chronological and biological age. Injury incidence tends to increase with increasing age, and it is higher in matches and tournaments than in training. The growth spurt represents a period of high vulnerability in young male soccer players. However, further studies should clarify whether sex and maturity status have an impact on injury incidence. Male soccer players seem to be more prone to muscle strains and ligament sprains affecting particularly the ankle and thigh. Female players meanwhile suffer more ligament sprains located in the ankle and knee. Severe injuries are less frequent but tend to increase in older players. Therefore, the injury incidence may be

high in young soccer players, but it depends on numerous factors including age, sex, and maturity. Knowledge of individual characteristics is needed in order to promote individualised prevention programmes.

Future studies should try to further investigate how the injury rate changes during the different development periods of young soccer players. Moreover, we observed a wide disparity between the studies conducted in male compared to female soccer. Therefore, considering the real absence of consistent investigation, future studies should focus more on epidemiological analysis of female soccer players.

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The authors have declared that no conflicts/competing interests exist.

Contributorship

MM and AT was responsible for the conception and design of the study. MM, AT and AF conducted the literature review. MM, AT and MG contributed to data collection and interpretation. The article was written by MM and AT. All authors contributed to the reviewing of the manuscript.

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Injury incidence and risk factors in youth soccer players: a systematic literature review. Part II: Intrinsic and extrinsic risk factors

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ABSTRACT: Injury is defined as a complex phenomenon determined by the non-linear interaction of several intrinsic and extrinsic factors. The objective of the present study was to perform a systematic literature review on the injury risk factors in young soccer players. After electronic database searching, articles in line with the inclusion criteria were selected for the systematic review. Injury risk factor data were extracted and grouped in intrinsic and extrinsic risk factors. The main findings of the current review are as follows: (1) alteration in neuromuscular control such as limb asymmetry and dynamic knee valgus are important intrinsic risk factors; (2) maturation status may impair neuromuscular control and increase the risk of injury; (3) fatigue and poor recovery contribute to the onset of overuse injuries; (4) the impact of anthropometric factors is still unclear; (5) previous injuries increase the risk of re-injuries; (6) highly skilled players are more exposed to risk of injuries; (7) high external workloads increase the risk of injuries; (8) playing position, as well as sport specialization, exposes young soccer players to greater injury risk. Many factors (e.g., neuromuscular control, training load, maturity status) can modify the susceptibility to injury in young soccer players. Being aware of the complex interaction between these factors is essential to identify players at higher risk of injury, develop adequate prevention strategies, and from a scientific point of view move from a reductionist to a complex system approach.

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INTRODUCTION

Sports practice induces several positive effects on both psychological (e.g. self-esteem, emotional regulation, social skills) [1] and physical spheres (e.g. body composition, aerobic fitness, muscular strength) [2]. Nevertheless, despite the numerous health benefits, sports practice may be dangerous in terms of accidents and injuries [3]. Soccer, considered a safe sport [4–6], was reported to have a higher injury rate compared to other team sports, such as rugby, basketball, and American football [7].

Soccer is characterised by high intensity changes of direction, sprints, and jumps [8]. In addition, nowadays soccer matches lead to greater intensity and physical efforts than in the past [9], and consequently more intense training is required to improve the physical fitness demands [10]. These factors expose young soccer players to a higher risk of injuries, compared to adult players. Indeed, in contrast to adults, young athletes experience maturation processes characterised by rapid changes in body size, shape, composition, and hormonal release [11]. All these factors, together with a concomitant alteration in motor coordination and neuromuscular control [12], could increase the susceptibility to injury in young soccer players.

Thus, considering also the negative effects related to youth soccer practice (e.g., dropout, talent development stagnation), it is important to develop prevention strategies. However, the introduction of prevention measures represents the third step of a more complex process known as "the sequence of prevention" [13]. According to this model, the first step consists in identifying and describing sport injuries (e.g., incidence, severity). The second step is to analyse the risk factors and mechanisms underlying injuries, while, the third step allows prevention strategies to be introduced and subsequently their effect on the athletes to be monitored [13]. Regarding the first step, our companion review (part I) [108] aimed to provide epidemiological information of injuries, reporting injury incidence, severity, types, mechanism, and anatomical location. The purpose of this second review (part II) is to identify the injury risk factors.

In general, an injury is a complex phenomenon determined by the interaction of different factors, as explained by Meeuwisse's dynamic model [14]. According to this model, the risk factors are traditionally classified as intrinsic (e.g. body composition, gender) and extrinsic (e.g. turf type, sports equipment) ones.

The interaction between intrinsic and extrinsic risk factors predisposes soccer players to injury; however, the presence of an inciting event such as playing position or match schedule represents the real final factor that causes the onset of the injury [14]. Thus, it is unlikely that a single factor is the cause of injury, but rather the interaction between player and environment. Therefore, it is crucial for coaches and physical trainers to be aware of all the injury risk factors, particularly those that could be modified through training and behavioural norms (modifiable risk factors).

Previous authors have already attempted to review injury risk factors in soccer, but these studies are limited to specific injury types such as anterior cruciate ligament tear [15] or hamstring injuries [16].

Therefore, the aim of this review is to identify all the potential injury risk factors and their interactions in young soccer players to provide a general overview for sport practitioners.

MATERIALS AND METHODS

Search strategy

We conducted a systematic review of the literature according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [17]. The eligible studies were searched by two independent researchers consulting the following electronic databases: ERIC (Educational Resources Information Center), PubMed/NCBI (National Center for Biotechnology Information, U.S. National Library of Medicine), Scopus, SPORTDiscus via EBSCOhost and Web of Science (WOS), from inception up to the end of February 2021. In each database, the search was performed as follows: [soccer OR football] AND [youth OR young OR adolescen*] AND [injur* OR risk of injury OR impairments].

All the articles were collected using Excel Software (Microsoft Excel 2016, Microsoft Corporation, Washington, USA) to manage duplicates and screening procedures.

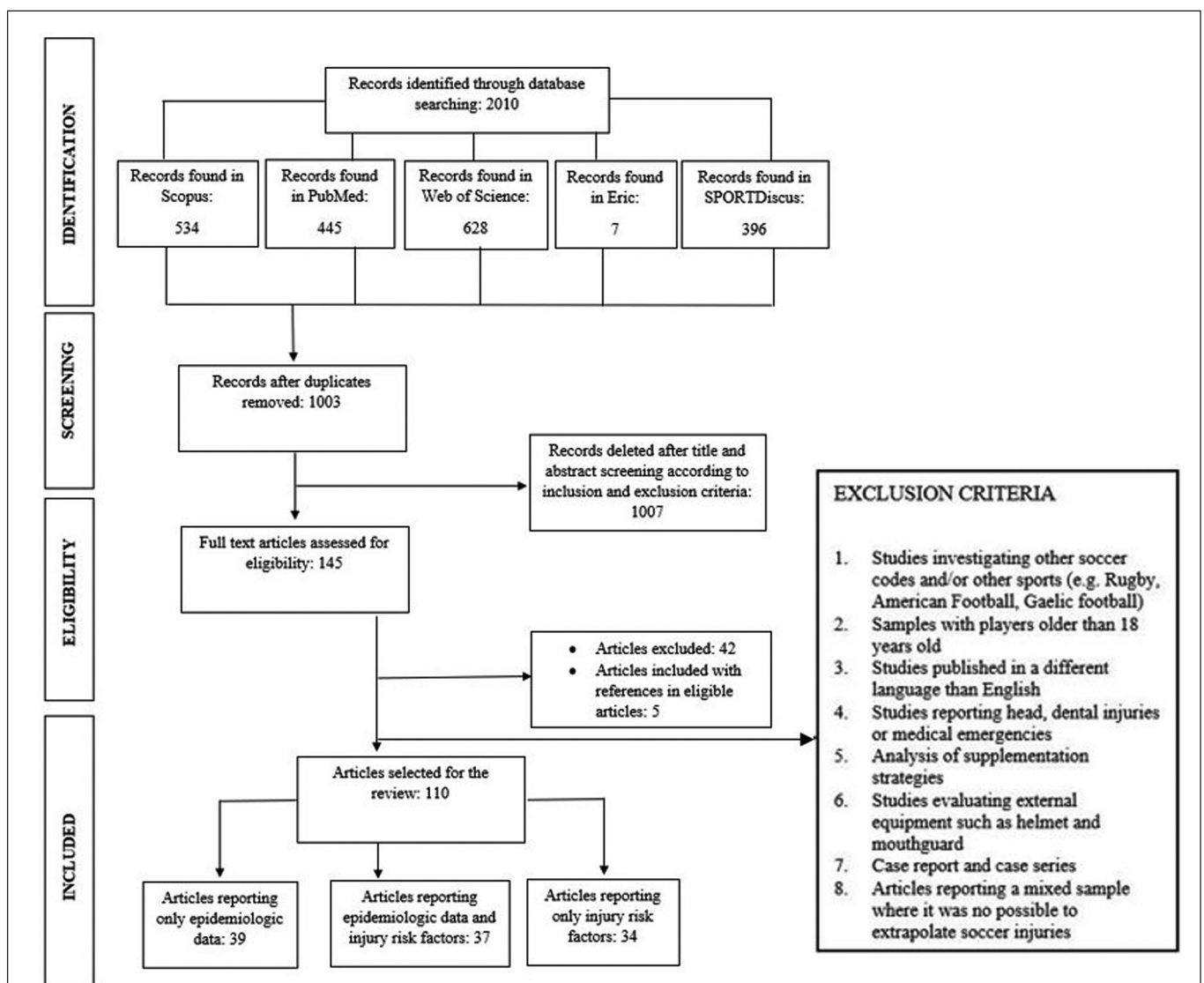


FIG. 1. PRISMA Flow Chart.

Inclusion and exclusion criteria

The systematic literature review focused on two main topics: injury epidemiological data and injury risk factors in youth soccer players; thus, the inclusion criteria were general and specific for each topic.

General inclusion criteria: (1) published original data (i.e., abstracts, books, reviews, systematic reviews, and meta-analysis were excluded); (2) published in the English language; (3) published in a peer-reviewed scientific journal; (4) articles found in an electronic database up to the 28th of February 2021. Finally, to allow the identification of relevant papers not found during the electronic search, the snowballing technique was applied.

Inclusion criteria for injury epidemiological data: (1) samples of young male and female soccer players (7–18 years old); (2) articles which collected at least one outcome related to injury epidemiological data: injury incidence, injury type, severity, re-injury, anatomic location (3) prospective or retrospective studies.

Inclusion criteria for injury risk factors: (1) samples of young male and female soccer players (5–18 years old); (2) articles that analysed risk factors connected to the onset of injury; (3) articles identifying injury predisposition factors (4) prospective, retrospective, cross-sectional studies, randomized control trials (RCT).

Exclusion criteria are presented in Figure 1.

Study selection process

Electronic database searching was initially performed by one reviewer (MM). Then, deletion of duplicates was done by two reviewers (MM and AT). After this step, considering the high amounts of articles identified, a preliminary title screening was conducted, and the selected articles were subjected to abstract screening according to the inclusion criteria previously mentioned.

The full text of the articles identified for eligibility was analysed by three reviewers (AT, MG, MM) for the two main topics: injury epidemiological data and injury risk factors. Thus, the included articles were organised separately according to the area of interest and subjected to the data extraction process conducted by two reviewers (AT, MM).

Methodological quality of individual studies

Following the same procedure reported by Hume et al. [18], two authors (MM, AT) independently assessed each article reported in the current review using a 6-item custom methodological quality assessment scale. The six items were (P1) study design (0 = cross sectional, retrospective cohort study, 1 = prospective cohort study, randomized-case control, quasi-experimental); (P2) participants' level (0 = non-elite, 1 = elite/sub-elite); (P3) sample size (0 = less than 20 subjects recruited, 1 = more than 20 subjects recruited); (P4) association with injury onset (0 = not investigated, 1 = investigated); (P5) Number of risk factors investigated (0 = only one, 1 = more than one); (P6) Injury risk results (0 = not clearly reported, 1 = clearly reported and tabulated). The evaluation process together with the final quality score is presented in Table 1. The quality score calculated was not considered as an exclusion criterion.

RESULTS

Search results

Of the 2010 articles found through electronic database searching, only 110 articles met the inclusion criteria (Figure 1). Then, among these, the following articles [5, 7, 19–87] reported injury risk factors and were organised in the present review as follows:

TABLE 1. General information of studies selected

REFERENCES	STUDY DESIGN (QUALITY SCORE)	P1	P2	P3	P4	P5	P6	COUNTRY	DURATION OF DATA COLLECTION	LEVEL OF YOUNG PLAYERS	SEX OF PLAYERS
Aoki et al. [39]	Prospective cohort study (5)	1	0	1	1	1	1	Japan	1 season	Non-elite	Male
Bacon and Mauger [54]	Prospective cohort study (6)	1	1	1	1	1	1	UK	2 seasons	Elite	Male
Bastos et al. [45]	Retrospective study (4)	0	0	1	1	1	1	Brazil	Not available	Non-elite	Male
Bell et al. [67]	Retrospective survey (4)	0	0	1	1	1	1	USA	Not available	Non-elite	Male/Female
Bianco et al. [19]	Prospective cohort study (4)	1	1	1	1	0	0	Italy	1 season	Elite	Male
Bowen et al. [21]	Prospective cohort study (6)	1	1	1	1	1	1	UK	2 seasons	Elite	Male
Brink et al. [5]	Prospective cohort study (6)	1	1	1	1	1	1	The Netherlands	2 seasons	Elite	Male
Bult et al. [43]	Prospective cohort study (5)	1	1	1	1	0	1	The Netherlands	3 seasons	Elite	Male
Clausen et al. [63]	Prospective cohort study (5)	1	0	1	1	1	1	Denmark	1 season	Non-elite	Female
Cloke et al. [75]	Prospective cohort study (5)	1	1	1	1	1	0	UK	5 seasons	Elite	Male
Cloke et al. [78]	Prospective cohort study (5)	1	1	1	1	1	0	UK	6 seasons	Elite	Male
De Ridder et al. [36]	Prospective cohort study (6)	1	1	1	1	1	1	Belgium	3 seasons	Elite	Male
De Ste Croix et al. [22]	Quasi-experimental design (4)	1	1	1	0	0	1	UK	Not available	Elite	Female
Engin & Arslan [84]	Retrospective study (5)	0	1	1	1	1	1	Turkey	Not available	Elite	Male
Emery & Meeuwisse [60]	Prospective cohort study (5)	1	0	1	1	1	1	Canada	20 weeks	Non-elite	Male/Female
Emery et al. [33]	Prospective cohort study (5)	1	0	1	1	1	1	Canada	13 weeks	Non-elite	Male/Female

TABLE 1. Continue.

REFERENCES	STUDY DESIGN (QUALITY SCORE)	P1	P2	P3	P4	P5	P6	COUNTRY	DURATION OF DATA COLLECTION	LEVEL OF YOUNG PLAYERS	SEX OF PLAYERS
Ferreira et al. [37]	Cross-sectional study (3)	0	1	1	0	1	0	Brazil	Not available	Elite	Male
Frisch et al. [27]	Prospective cohort study (5)	1	0	1	1	1	1	Luxemburg	1 season	Non-elite	Male
Froholdt et al. [50]	Prospective cohort study (5)	1	0	1	1	1	1	Norway	1 season	Non-elite	Male/Female
Frome et al. [68]	Retrospective survey (4)	0	0	1	1	1	1	USA	Not available	Non-elite	Male
Haag et al. [56]	Cross-sectional study (4)	0	0	1	1	1	1	Germany	Not available	Non-elite	Male/Female
Hägglund & Waldén [58]	Prospective cohort study (5)	1	0	1	1	1	1	Sweden	1 season	Non-elite	Female
Hoff & Martin [53]	Retrospective survey (3)	0	0	1	1	0	1	USA	Not available	Non-elite	Male/Female
Isik et al. [73]	Retrospective survey (5)	1	1	1	0	1	1	Turkey	Not available	Elite	Male
John et al. [40]	Cross-sectional study (2)	0	0	1	0	0	1	Germany	Not available	Non-elite	Male
Johnson et al. [46]	Prospective cohort study (5)	1	1	1	1	0	1	UK	6 seasons	Elite	Male
Johnson et al. [35]	Prospective cohort study (6)	1	1	1	1	1	1	UK	2 seasons	Elite	Male
Kemper et al. [25]	Prospective cohort study (6)	1	1	1	1	1	1	The Netherlands	1 season	Elite/Non-elite	Male
Ko et al. [34]	Prospective cohort study (5)	1	0	1	1	1	1	USA	1 season	Non-elite	Male
Koenig & Puckree [42]	Cross-sectional study (4)	0	0	1	1	1	1	South Africa	Not available	Non-elite	Female
Kofotolis [24]	Prospective cohort study (5)	1	0	1	1	1	1	Greece	1 season	Non-elite	Male
Kucera et al. [41]	Prospective cohort study (4)	1	0	1	1	0	1	USA	4 seasons	Non-elite	Male/Female
Le Gall et al. [28]	Prospective cohort study (5)	1	1	1	1	0	1	France	10 seasons	Elite	Male
Lehnert et al. [52]	Quasi-experimental design (4)	1	1	0	0	1	1	Czech Republic	Not available	Elite	Male
Lehnert et al. [30]	Quasi-experimental design (5)	1	1	1	0	1	1	Czech Republic	Not available	Elite	Male
Lukášek et al. [44]	Cross-sectional study (1)	0	0	0	0	0	1	Czech Republic	Not available	Non-elite	Male
Matrone et al. [86]	Prospective cohort study (5)	1	1	1	1	0	1	Qatar	4 seasons	Elite	Male
Nagle et al. [76]	Prospective cohort study (3)	1	0	1	1	0	0	USA	8 seasons	Non-elite	Male/Female
Nakazawa et al. [74]	Cross-sectional study (2)	0	0	0	1	0	1	Japan	Not available	Non-elite	Male
Namazi et al. [70]	Prospective cohort study (6)	1	1	1	1	1	1	Iran	1 season	Elite	Male
Nguyen et al. [49]	Longitudinal descriptive study (3)	1	0	0	0	1	1	USA	3 seasons	Non-elite	Female
O'Kane et al. [65]	Prospective cohort study (6)	1	1	1	1	1	1	USA	4 seasons	Elite	Female
O'Kane et al. [48]	Prospective cohort study (5)	1	1	1	1	1	1	USA	2 seasons	Elite	Female
O'Kane et al. [61]	Prospective cohort study (6)	1	1	1	1	0	1	USA	2 seasons	Elite	Female
Price et al. [79]	Prospective cohort study (5)	1	1	1	1	1	0	UK	2 seasons	Elite	Male
Räisänen et al. [47]	Prospective cohort study (4)	1	0	1	1	0	1	Finland	1 year	Non-elite	Male/Female
Raya-González et al. [31]	Prospective cohort study (6)	1	1	1	1	1	1	Spain	1 season	Elite	Male
Read et al. [20]	Prospective cohort study (6)	1	1	1	1	1	1	UK	1 season	Elite	Male
Read et al. [23]	Cross-sectional study (4)	0	1	1	0	1	1	UK	Not available	Elite	Male
Read et al. [80]	Cross-sectional and prospective cohort study (6)	1	1	1	1	1	1	UK	1 season	Elite	Male
Rolls and George [72]	Prospective cohort study (6)	1	1	1	1	1	1	UK	1 season	Elite	Male
Rommers et al. [83]	Prospective cohort study (6)	1	1	1	1	1	1	Belgium	1 season	Elite	Male
Rommers et al. [87]	Prospective cohort study (5)	1	1	1	1	0	1	Belgium	2 seasons	Elite	Male
Rosenbaum et al. [77]	Prospective cohort study (4)	1	0	1	1	0	1	USA	2-day tournament	Non-elite	Male/Female
Rössler et al. [59]	Prospective cohort study (5)	1	0	1	1	1	1	Czech Republic and Switzerland	2 seasons	Non-elite	Male/Female
Sanz et al. [81]	Prospective cohort study (5)	1	1	1	1	1	0	Spain	1 season	Elite	Male
Schwebel et al. [29]	Prospective cohort study (4)	1	0	1	1	1	0	USA	8 weeks	Non-elite	Male
Sieland et al. [85]	Prospective cohort study (6)	1	1	1	1	1	1	Germany	2 seasons	Elite	Male
Soligard et al. [26]	Prospective cohort study (4)	1	0	1	1	0	1	Norway	1 season	Non-elite	Female
Steffen et al. [62]	Prospective cohort study (5)	1	0	1	1	1	1	Norway	1 season	Non-elite	Female
Steffen et al. [64]	Prospective cohort study (5)	1	0	1	1	1	1	Norway	8 months	Non-elite	Female
Sugimoto et al. [57]	Cross-sectional study (4)	0	0	1	1	1	1	USA	Not available	Non-elite	Female
Van der Sluis et al. [66]	Prospective cohort study (5)	1	1	1	1	0	1	The Netherlands	3 seasons	Elite	Male
Van der Sluis et al. [38]	Prospective cohort study (5)	1	1	1	1	0	1	The Netherlands	3 seasons	Elite	Male
Venturelli et al. [7]	Prospective cohort study (6)	1	1	1	1	1	1	Italy	1 season	Elite	Male
Watson et al., [55]	Prospective cohort study (5)	1	0	1	1	1	1	USA	20 weeks	Non-elite	Female
Watson et al. [69]	Prospective cohort study (5)	1	0	1	1	1	1	USA	20 weeks	Non-elite	Female
Westbrook et al. [82]	Cross-sectional study (3)	0	0	1	0	1	1	USA	Not available	Non-elite	Female
Wollin et al. [51]	Quasi-experimental design (4)	1	1	0	0	1	1	Australia	3 days	Elite	Male
Wright et al. [71]	Quasi-experimental design (4)	1	1	0	0	1	1	UK	Not available	Elite	Female
Zebis et al. [32]	Cluster-randomized controlled trial (4)	1	0	1	1	0	1	Denmark	1 season	Non-elite	Female

- Intrinsic risk factors (neuromuscular control, physiological and psychological factors, biological and anthropometric factors, previous injuries, technical and tactical skills).
- Extrinsic risk factors (playing surface, shoes, external workload, playing position, sport specialization).

Injury risk factors

Intrinsic risk factors

Intrinsic risk factors are defined as individual biological and psychosocial characteristics which make athletes prone to injury [88]. A total of fifty-nine articles [5, 7, 20, 22–27, 29–31, 33–43, 45–52, 55–66, 68–74, 78–84, 86, 87] reported intrinsic injury risk factors.

Neuromuscular control

Twenty-six articles investigated neuromuscular control in young soccer players [20, 22, 23, 27, 30, 33, 34, 36, 37, 40, 42, 47–49, 51, 52, 58, 61, 70, 71, 73, 74, 78, 79, 82, 84]. Among these, four studies [22, 30, 52, 71] used the SAFT protocol (Prozone) to replicate soccer-specific fatigue and to analyse change in pre- and post-test neuromuscular control. Lehnert et al. [30, 52] in two different studies observed a reduction in both absolute and relative leg stiffness. No changes were observed in isokinetic strength of the hamstrings and quadriceps, or in the hamstring/quadriceps ratio. In one study [52], the authors also reported a decrease in the reactive strength index. De Ste Croix et al. [22] observed an electromechanical delay (EMD) longer in the U13 age group compared with U15 and U17 after the SAFT protocol. However, the same test did not show alteration in knee kinematics during a single leg drop jump and countermovement jump in female soccer players [71].

Instead, Wollin et al. [51] investigated how fatigue, induced by congested soccer matches, impaired neuromuscular control. The authors detected a transient reduction in hamstring strength, with a recovery time needed superior to 48 hours.

De Ridder et al. [36] identified that a low strength level of the posterior chain hip muscle was associated with ankle sprains, and similarly low hip and knee muscle strength was significantly related to lower limb injuries [70]. Regarding this issue, Nguyen et al. [49] were interested in investigating whether changes in the hip strength occurred when youth female soccer players increased in age. The authors did not find changes in isometric hip strength but in the hip range of motion, particularly, they found an increase in passive hip abduction and in passive hip internal rotation.

Four studies [47, 48, 61, 82] investigated knee kinematics during a landing task [48, 61] and during single leg squat [47]. O'Kane et al. [61] found that the normalised knee separation (NKS) on landing that was in the $\leq 10^{\text{th}}$ percentile increased the risk of knee injury in female soccer players. The results are in agreement with a previous study [48], which however found an association between NKS and knee injury, but only in postmenarchal players. Similarly, Westbrook et al. [82] found a greater peak knee abduction angle during a double-leg countermovement jump task in post-pubertal

female players. However, Räsänen et al. [47] did not identify the frontal knee projection angle (FKPA) during a single leg squat as an injury risk factor.

Read et al. [20] revealed single leg countermovement jump (SL-CMJ) landing force asymmetry as the most relevant injury risk factors, without significant difference for the single leg hop for distance (SLHD) and tuck jump assessment (TJ). However, SLHD was identified as a potential risk factor by Sieland et al. [85]. Static and dynamic balance tests [27, 33, 42] were not sensitive to identify injury risk conditions. Furthermore, three studies [47, 78, 79] found most of the injuries located in the dominant leg. In contrast, Hägglund & Waldén [58] reported a higher prevalence of ACL injuries in the non-dominant leg.

Five studies [34, 40, 74, 80, 84] used a functional test to evaluate neuromuscular control. First, Ko et al. [34] identified the posterior-lateral and posterior-medial score of the star excursion balance test (SEBT) as associated with risk of injury. Similarly, John et al. [40] and Read et al. [80] performed the Y-Balance test (YBT) with young male soccer athletes. Read et al. [80] found a significant association between injury and anterior reach scores. Then, John et al. [40] found a lower score in players with higher maturity offset; however, they did not investigate the association between the test and risk of injuries. Nakazawa et al. [74] found a difference between injured and non-injured groups in the sideways bench test. Finally, Engin & Arslan [84] investigated the association between functional movement screening (FMS) score and risk of musculoskeletal injuries without finding any significant association.

Physiological and psychological risk factors

Thirteen articles [5, 7, 22, 27, 30, 31, 33, 51, 52, 55, 63, 64, 69] investigated physiological and psychological risk factors.

Five studies [22, 30, 51, 52, 71] focused on the effect of fatigue on physiological parameters. In general, fatigue produced a worsening in hamstring activation [22], reactive strength and stiffness [30, 52], and isometric hamstring strength [51]. Moreover, physical fatigue, assessed through a questionnaire [27], was associated with injuries (HR = 2.32) in young players.

Three studies [5, 31, 69] evaluated the stress state resulting from training and the link with injuries. Brink et al. [5] found an association between internal load (S-RPE), monotony, and strain with traumatic injuries. Furthermore, several subscales of the REST-Q questionnaire, reported in Table 2, were related to illness risk. Likewise, Watson et al. [69] found an association between training load and risk of injuries and illnesses. In contrast, Raya-González et al. [31] did not find a significant association between weekly training load and risk of injuries.

Three studies [7, 33, 54] evaluated aerobic fitness of the players. Two studies [7, 33] did not find any link with injuries, while Watson et al. [55] observed that players' lower preseason aerobic fitness levels were associated with a higher risk of subsequent in-season injury and illness.

TABLE 2. Summary of the risk factors related to injuries in young soccer players.

STUDY	RISK FACTORS EXAMINED	SIGNIFICANT RISK FACTOR IDENTIFIED	STATISTICAL RESULTS	NON-SIGNIFICANT RISK FACTORS	SAMPLE SIZE AND INJURY RATE	MAIN TOPIC AREA
Read et al. [20]	- Chronological age - Maturity offset - Neuromuscular control test: • single leg hop for distance (SLHD) • 75% of maximum hop and stick (75%Hop) • single leg countermovement jump (SLCMJ) • tuck jump assessment (TJ)	1. SLCMJ peak landing vertical ground reaction force asymmetry 2. Lower right leg SLCMJ peak landing vertical ground reaction force relative to body weight 3. Maturational Offset 4. Advanced chronological age	1. U11-U12's OR = 0.90 $p = 0.04$ - U15-U16's OR = 0.91 $p < 0.001$ 2. U15-U16's OR = 0.36 $p = 0.03$ 3. U13-U14's OR = 0.58 $p = 0.04$ 4. U18's OR = 3.62 $p = 0.04$	- single leg hop for distance (SLHD) - 75% of maximum hop and stick (75%Hop) - tuck jump assessment (TJ)	356 elite male youth soccer players were monitored for 10 months (99 sustained a non-contact lower extremity injury)	NEUROMUSCULAR CONTROL
Sieland et al. [85]	- Age - Drop Jump - Countermovement jump - Single-leg hop for distance - Side asymmetry-single-leg hop for distance - Sit-and-Reach - Knee extension - Knee flexion - Sprint 10 m - Sprint 30 m - Zig-Zag test without ball - Zig-Zag test with ball	1. Age 2. Side asymmetry-single-leg hop for distance	1. Age $r = 0.191$ $p = 0.006$ 2. Side asymmetry-single-leg hop for distance $p = 0.08$	- Drop Jump - Countermovement jump - Single-leg hop for distance - Sit-and-Reach - Knee extension - Knee flexion - Sprint 10 m - Sprint 30 m - Zig-Zag test without ball - Zig-Zag test with ball	93 players were followed during two seasons (125 injuries were recorded)	
Engin & Arslan [84]	- FMS score - Asymmetry - Age	1. Age	1. Age OR = 1.57 $P = 0.002$	- FMS score - Asymmetry	57 elite male youth soccer players (27 musculoskeletal injuries were recorded)	
De Ste Croix et al. [22]	- Neuromuscular control of knee after soccer-specific fatigue in elite female youth soccer: - Surface electromyography (EMD) was used to investigate effect of fatigue on hamstrings during eccentric actions at 60, 120 and 180°/s	1. EMD was significantly longer in U13 age group compared with U15 and U17	1. 158 ± 66 ms vs 113 ± 39 $p = 0.021$ (U13vsU15) 158 ± 66 ms vs 120 ± 40 $p = 0.021$ (U13 vs U17)	- No significant main effects for the different muscles (semitendinosus, biceps femoris and gastrocnemius) - No significant main effect for the different velocity (60, 120 and 180°/s)	36 young female soccer players participated to the study	NEUROMUSCULAR CONTROL
Read et al. [23]	- Biological maturation (intrinsic risk factors) - Single leg countermovement jump (SLCMJ) height (intrinsic risk factors) - Peak vertical landing forces (pVGRF) (intrinsic risk factors) - Knee valgus (intrinsic risk factors) - Trunk side flexion (intrinsic risk factors)	1. Vertical jump height and absolute p VGRF increased linearly with each stage of maturation 2. Higher landing forces were recorded on the left leg in circa versus post-PHV 3. Significantly less knee valgus was found in post-PHV compared to pre-PHV on the left leg 4. Post-PHV players displayed greater lateral trunk flexion angles on the left leg compared to circa-PHV	1. Cohen's d effect sizes = 0.85–2.35 $p < 0.001$ 2. $d = -0.40$ $p < 0.05$ 3. $d = 0.67$ $p < 0.05$ 4. $d = 0.85$ $p < 0.05$	- No differences were shown for knee valgus on the right leg	400 elite male youth soccer players took part in the study	
Read et al. [80]	- Age - Height - Y-balance score	1. Y-balance Left (%leg length) 2. Y-balance right 3. Age	1. Y-balance Left (%leg length) OR = 0.94, 95% CI 0.91 to 0.98, $p < 0.001$ 2. Y-balance Right OR = 1.06, 95% CI 1.0 to 1.10, $P < 0.05$ 3. Age OR = 1.49, 95% CI 1.04 to 2.13, $P < 0.05$	- Height	346 elite male youth soccer players.	NEUROMUSCULAR CONTROL
Lehnert et al. [30]	- The parameters were assessed after SAFT protocol: • Reactive strength (RSI) • Absolute leg stiffness • Relative leg stiffness - Isokinetic strength	1. Reactive strength (RSI) 2. Absolute leg stiffness 3. Relative leg stiffness	1. % change = 7.5 $p < 0.01$ 2. % change = -8.1 $p < 0.01$ 3. % change = -6.4 $p < 0.01$	- Isokinetic strength	20 elite youth soccer players took part in the study	

TABLE 2. Continue.

STUDY	RISK FACTORS EXAMINED	SIGNIFICANT RISK FACTOR IDENTIFIED	STATISTICAL RESULTS	NON-SIGNIFICANT RISK FACTORS	SAMPLE SIZE AND INJURY RATE	MAIN TOPIC AREA
O'kane et al. [48]	- Normalized knee separation during drop jump (NKS) at prelanding, landing and take-off	Among postmenarchal players: 1. NKS $\leq 10^{\text{th}}$ percentile (most extreme valgus) at prelanding and landing, significantly increased lower extremity injury 2. NKS $\leq 10^{\text{th}}$ percentile (most extreme valgus) at prelanding and landing, significantly increased knee injury 3. NKS $\leq 10^{\text{th}}$ percentile (most extreme valgus) during take-off, significantly increased lower extremity injury 4. NKS $\leq 10^{\text{th}}$ percentile (most extreme valgus) during take-off, significantly increased knee injury	1. RR = 1.92 95% CI 1.17 to 3.15 2. RR = 3.62 95% CI 1.18 to 11.09 3. RR = 1.80 95% CI 1.01 to 3.23 4. RR = 1.66 95% CI 1.04 to 2.64	- Among premenarchal players, there was no statistically significant association between NKS at prelanding, landing and take-off and the risk of lower extremity or knee injury	351 female youth soccer players were followed for 1 season (173 lower extremity injuries, with 43 knee injuries, were recorded)	NEUROMUSCULAR CONTROL
Ko et al. [34]	- Age - Height - Body mass - BMI% - Star Excursion Balance Test (SEBT): • Anterior reach direction (AN) • Posterior-medial reach direction (PM) • Posterior-lateral (PL) reach direction - Single-Leg Hop Test (SLHT)	1. SEBT-PM 2. SEBT-PL 3. SLHT	1. OR = 16.61 Cohens d = 1.15 $p < 0.05$ 2. OR = 20.88 Cohens d = 1.31 $p < 0.05$ 3. OR = 32.53 Cohens d = 1.20 $p < 0.05$	- Age - Height - Body mass - BMI% - SEBT-AN	64 players were followed during one season (12 players sustained ankle sprain)	NEUROMUSCULAR CONTROL
De Ridder et al. [36]	- Body size dependencies and anterior chain/horizontal plan hip muscle forces - Posterior chain hip muscle forces - Hip adduction muscle force - Hip abduction muscle force	1. Higher posterior chain hip muscle forces produced significant reduction in ankle sprains	1. HR = 0.331 95% CI 0.123 to 0.890 $p < 0.05$	- Body size dependencies and anterior chain/horizontal plan hip muscle forces - Hip adduction muscle force - Hip abduction muscle force	133 male youth soccer players were followed over 3 seasons (12 players sustained a lateral ankle sprain)	NEUROMUSCULAR CONTROL
Räsänen et al. [47]	- Frontal plane knee projection angle (FPKPA) during the single-leg squat			- Frontal plane knee control in the single-leg squat was not associated with lower extremity injuries	558 players were recruited and monitored for 20 weeks (285 acute lower extremity injuries were reported)	
Lehnert et al. [52]	- Reactive strength index (RSI) - Leg stiffness - Isokinetic dynamometry with integrated sEMG	1. RSI 2. Absolute leg stiffness 3. Relative leg stiffness 4. Muscle activation decreased in Rectus femoris, vastus medialis, semimembranosus	1. ES = 0.40 $p < 0.05$ 2. ES = 0.55 $p < 0.05$ 3. ES = 0.68 $p < 0.05$ 4. ES = 0.33–0.97 $p < 0.05$	- H/Q FUNC did not change - Muscle activation of vastus lateralis and biceps femoris did not change	18 elite youth soccer players took part in the study	NEUROMUSCULAR CONTROL
Koenig & Puckree [42]	- Sway index (SI) - Limits of stability direction control (LOS)			- Sway index (SI) Limits of stability direction control (LOS)	80 adolescent female soccer players took part in the study	
Nguyen et al. [49]	- Hip range of motion (ROM): • Passive hip internal rotation (IR) • Passive hip external rotation (ER) • Passive hip abduction (ABD) • Passive hip adduction (ADD) - Isometric hip strength: • Isometric hip abduction (ABD) • Isometric hip extension (EXT)	1. Hip ABD ROM significantly increased 2. Hip ADD ROM significantly decreased 3. Hip IR ROM increased 4. Hip ER ROM decreased	1. $p < 0.001$ 2. $p = 0.009$ 3. $p = 0.001$ 4. $p < 0.001$	- Isometric hip ABD Isometric hip EXT	14 female youth soccer players were recruited in the study	NEUROMUSCULAR CONTROL

TABLE 2. Continue.

STUDY	RISK FACTORS EXAMINED	SIGNIFICANT RISK FACTOR IDENTIFIED	STATISTICAL RESULTS	NON-SIGNIFICANT RISK FACTORS	SAMPLE SIZE AND INJURY RATE	MAIN TOPIC AREA
John et al. [40]	- Balance error scoring system (BESS) - Y-Balance test (YBT) • Anterior reach direction • Posteromedial reach direction - Posterolateral reach direction	1. Total BESS score was significantly lowest in participants with the lowest maturity offset 2. Anterior reach direction of the right leg was lower in players with higher maturity offset 3. Anterior reach direction of the left leg was lower in players with higher maturity offset 4. Posteromedial reach direction of the left leg was lower in players with higher maturity offset	1. $b = 2.195$ $p = 0.022$ 2. $b = -0.022$ $p = 0.023$ 3. $b = -0.024$ $p = 0.015$ 4. $b = -0.29$ $p = 0.020$	- Posterolateral of right and left leg reach direction of YBT - Posteromedial of right direction of YBT	101 male youth soccer players were recruited	NEUROMUSCULAR CONTROL
O'Kane et al. [61]	- Joint hypermobility - Hamstring strength - Quadriceps strength - Hip Strength - Normalized knee separation during drop-jump test (NKS) - Playing in another soccer team - Position played in the last month - Participation in another sports team	1. NKS on landing in the $\leq 10^{\text{th}}$ percentile (most valgus appearing) increased lower extremity injuries 2. NKS on landing in the $\leq 10^{\text{th}}$ percentile (most valgus appearing) increased knee injury 3. Playing in another soccer team increased knee overuse injury	1. $RR = 2.24$ 95% CI 1.20 to 4.19 2. $RR = 3.2$ 95% CI 1.52 to 6.71 3. $RR = 2.5$ 95% CI 1.08 to 5.35	- Increase in hamstring strength reduced overuse knee injury - Increase in quadriceps strength reduced overuse knee injury - Increase in hip flexor and external rotation reduced overuse knee injury - Joint hypermobility - Position played in the last month - Participation in another sports team	351 players were monitored over 4 seasons (83 lower extremity overuse injuries were recorded)	NEUROMUSCULAR CONTROL
Wollin et al. [51]	- Hamstring maximum voluntary isometric contraction (MVIC) - Perceived pain on isometric hamstring MVIC - Ankle dorsiflexion - Hip extension range of motion - Active knee extension (AKE) - Prone knee bend (PKB)	1. Hamstring strength significantly reduced 24h post-match 1 2. Hamstring strength significantly reduced 48h post-match 1 3. Hamstring strength significantly reduced 24h post-match 2 4. Pain increased moderately 24h post-match 1 5. Pain increased moderately 48h post-match 1 6. PKB reduced 24h post-match 1 7. PKB reduced 24h post-match 2 8. PKB reduced 48h post-match 2	1. Mean difference = --- 0.19 Nm/Kg $p = 0.001$ 2. Mean difference = ----- 0.16 Nm/kg $p = 0.002$ 3. Mean difference = ----- 0.17 Nm/kg $p = 0.012$ 4. $ES = 0.42$ $p = 0.02$ 5. $ES = 0.38$ $p = 0.036$ 6. Mean difference = -----2.7° $p = 0.002$ 7. Mean difference = -----1.5° $p = 0.044$ 8. Mean difference = -----2.7° $p = 0.023$	- Hamstring strength did not change 48 and 72h post-match 2 - There was no change in pain on match day 2, at 24, 48 and 72 post-match 2 - None of the other ROM outcome measures demonstrated a significant change during the 2-match congestion period	15 male elite youth soccer players took part in the study	NEUROMUSCULAR CONTROL

TABLE 2. Continue.

STUDY	RISK FACTORS EXAMINED	SIGNIFICANT RISK FACTOR IDENTIFIED	STATISTICAL RESULTS	NON-SIGNIFICANT RISK FACTORS	SAMPLE SIZE AND INJURY RATE	MAIN TOPIC AREA
Brink et al. [5]	- Internal load (Duration × RPE) (S-RPE)	1. Duration (Traumatic injury)	1. OR = 1.14	- Duration (Overuse)	53 elite soccer players were monitored over 2 seasons (320 injuries and 82 illness occurred)	PHYSIOLOGICAL AND PSYCHOLOGICAL RISK FACTORS
	- Monotony	2. Duration (Illness)	95% CI 1.06 to 1.23	- Load (Overuse injury, Illness)		
	- Strain	3. Load (Traumatic injury)	$p < 0.05$	- Monotony (Overuse injury, Illness)		
	- Recovery-stress state (REST-Q)	4. Monotony (Traumatic injury)	2. OR = 1.12	- Strain (Overuse injury, Illness)		
	• General stress	5. Strain (Traumatic injury)	95% CI 1.00 to 1.26	- REST-Q: the remaining subscales did not show any significant difference		
	• Sport-specific stress	6. REST-Q: emotional stress (Illness)	$p < 0.05$			
	• General recovery	7. REST-Q: Social stress (Illness)	3. OR = 1.01			
	- Sport-specific recovery	8. REST-Q: Conflicts/pressure (Illness)	95% CI 1.00 to 1.02			
		9. REST-Q: fatigue (Illness)	$p < 0.05$			
		10. REST-Q: Lack of energy (Illness)	4. OR = 2.59			
		11. REST-Q: Physical complaints (Illness)	95% CI 1.22 to 5.50			
		12. REST-Q: Social recovery (Illness)	$p < 0.05$			
		13. REST-Q: General well-being (Illness)	5. OR = 1.01			
		14. REST-Q: Sleep quality (Illness)	95% CI 1.00 to 1.01			
		15. REST-Q: Disturbed breaks (Illness)	$p < 0.05$			
		16. REST-Q: Emotional exhaustion (Illness)	6. OR = 2.27			
		17. REST-Q: Being in shape (Illness)	95% CI 1.43 to 3.61			
		18. REST-Q: Fitness/injury (Traumatic injury)	$p < 0.01$			
		19. REST-Q: Fitness/injury (Overuse injury)	7. OR = 2.59			
			95% CI 1.22 to 5.50			
			$p < 0.01$			
			8. OR = 1.69			
			95% CI 1.18 to 2.42			
			$p < 0.01$			
			9. OR = 1.48			
			95% CI 1.05 to 2.09			
			$p < 0.05$			
			10. OR = 1.92			
			95% CI 1.27 to 2.91			
			$p < 0.01$			
			11. OR = 1.88			
			95% CI 1.24 to 2.83			
			$p < 0.01$			
			12. OR = 0.66			
			95% CI 0.47 to 0.94			
			$p < 0.05$			
			13. OR = 0.57			
			95% CI 0.39 to 0.83			
			$p < 0.01$			
			14. OR = 0.58			
			95% CI 0.40 to 0.83			
			$p < 0.01$			
			15. OR = 1.51			
			95% CI 1.03 to 2.22			
			$p < 0.05$			
			16. OR = 1.47			
			95% CI 1.06 to 2.03			
			$p < 0.05$			
			17. OR = 0.56			
			95% CI 0.40 to 0.79			
			$p < 0.01$			
			18. OR = 1.29			
			95% CI 1.01 to 1.66			
			$p < 0.05$			
			19. OR = 1.46			
			95% CI 1.09 to 1.96			
			$p < 0.05$			

TABLE 2. Continue.

STUDY	RISK FACTORS EXAMINED	SIGNIFICANT RISK FACTOR IDENTIFIED	STATISTICAL RESULTS	NON-SIGNIFICANT RISK FACTORS	SAMPLE SIZE AND INJURY RATE	MAIN TOPIC AREA
Watson, et al. [69]	- Subjective well-being • Fatigue • Mood • Stress • Soreness • Sleep quality • Sleep hours - Training load (TL) • Daily • Prior day • Weekly • Monthly - Acute:Chronic	1. Mood (injuries) 2. Daily TL (injuries) 3. Prior day TL (injuries) 4. Weekly TL (illness) 5. Monthly TL (Illness)	1. OR = 0.12 95% CI 0.02 to 0.66 $p = 0.011$ 2. OR = 1.98 95% CI 1.43 to 2.78 $p < 0.001$ 3. OR = 1.38 95% CI 1.01 to 1.88 $p = 0.040$ 4. OR = 1.50 95% CI 1.13 to 2.00 $p = 0.005$ 5. OR = 1.54 95% CI 1.13 to 2.12 $p = 0.007$	- Fatigue - Stress - Soreness - Sleep quality - Sleep hours - Weekly TL (injuries) - Monthly TL (injuries) - Acute:Chronic TL (injuries) - Prior day TL (Illness) - Acute:Chronic TL (Illness)	75 youth female soccer players were monitored through 20-week season (36 injuries and 52 illness were recorded)	PHYSIOLOGICAL AND PSYCHOLOGICAL RISK FACTORS
Raya-González et al. [31]	- Sum of intrinsic training load for each week (WL) - Acute chronic workload ratio			- Sum of intrinsic training load for each week (WL) (intrinsic risk factor) - Acute chronic workload ratio (intrinsic risk factor)	21 players were followed during one season (27 non-contact injuries were recorded)	
Steffen et al. [64]	- Age - Height - Weight - BMI - Previous injury - Years of organized soccer play - Perception of success - Motivation climate - Life event - Sport anxiety - Brief cope	1. Previous injury 2. Years of organized soccer play 3. High level of perceived life stress 4. High level of perceived mastery climate 5. High level of life event	1. OR = 1.9 95% CI 1.4 to 2.5 $p < 0.001$ 2. RR = 1.12 95% CI 1.04 to 1.22 $p = 0.003$ 3. OR = 1.7 95% CI 1.3 to 2.2 $p < 0.001$ 4. OR = 1.34 95% CI 1.04 to 1.72 $p = 0.03$ 5. OR = 1.03 95% CI 1.01 to 1.05 $p = 0.02$	- Age - Height - Weight - BMI - Perception of success - Sport anxiety - Brief cope	1430 youth female players were followed during one season (380 injuries were recorded)	
Frisch et al. [27]	- Injury history - Physical fatigue - Emotional stress - Joint laxity - Anthropometric data - Hop for distance test (intrinsic factor) - Aerobic fitness - Maximal isokinetic tests - Static balance test - Dynamic balance test - Squat jump - Countermovement jump	1. Physical fatigue	1. HR = 2.32 95% CI 1.07 to 5.05 $p = 0.034$	- Injury history (intrinsic risk factor) - Emotional stress (intrinsic risk factor) - Joint laxity (intrinsic risk factor) - Anthropometric data (intrinsic risk factor) - Hop for distance test (intrinsic factor) - Aerobic fitness (intrinsic risk factor) - Maximal isokinetic tests (intrinsic risk factor) - Static balance test (intrinsic risk factor) - Dynamic balance test (intrinsic risk factor) - Squat jump (intrinsic risk factor) - Countermovement jump (intrinsic risk factor)	67 players were monitored during one season (163 injuries were registered)	PHYSIOLOGICAL AND PSYCHOLOGICAL RISK FACTORS

TABLE 2. Continue.

STUDY	RISK FACTORS EXAMINED	SIGNIFICANT RISK FACTOR IDENTIFIED	STATISTICAL RESULTS	NON-SIGNIFICANT RISK FACTORS	SAMPLE SIZE AND INJURY RATE	MAIN TOPIC AREA
Kemper et al. [25]	- Body mass - Height - Fat percentage - Growth in height (cm) - Alteration in body mass index (kg/m ²) Fat percentage and fat free mass index (kg/m ²)	1. Growth rates of at least 6 cm/month 2. Monthly BMI-increase of > 0.3 kg/m ² 3. Decrease in BMI-value of at least 0.4 kg/m ²	1. OR = 1.63 95% CI 1.06–2.52 $p = 0.03$ 2. OR = 1.61 95% CI 1.04–2.49 $p = 0.03$ 3. OR = 1.97 95% CI 1.18–2.76	- High fat percentage Fat free mass index (FFMI)	101 male youth players were followed during one season (134 injuries occurred). The injury incidence was 5.9/1000 hours)	BIOLOGICAL AND ANTHROPOMETRIC FACTORS
Materne et al. [86]	- Maturity status	1. Early-maturing vs normal-maturing players 2. Early-maturing vs mature players	1. HR = 1.26 95% CI, 1.11–1.42 $P < 0.001$ 2. HR = 1.35 95% CI, 1.17–1.56 $P < 0.001$		283 male elite soccer player were monitored during four consecutive seasons (a total of 1565 injuries were recorded)	
Johnson et al. [35]	- Maturity timing: • Pre-PHV • Circa-PHV • Post-PHV - Maturity status: • Early-maturer • On-time • Late-maturer	1. Circa-PHV versus Pre-PHV 2. Early/circa-PHV versus on-time/late/pre-PHV 3. On-time/late/circa-PHV versus on-time/late/pre-PHV	1. RR = 2.15 95% CI 1.37 to 3.38 $p < 0.001$ 2. RR = 2.42 95% CI 1.22 to 4.81 $p = 0.01$ 3. RR = 2.50 95% CI 1.53 to 4.07 $p = 0.0003$	- All other comparisons did not demonstrate significant differences	76 male young soccer players were monitored over two different seasons (88 injuries were recorded)	
Van der Sluis et al. [38]	Maturity timing (PHV)	1. Players who had their PHV at an older age had a higher incidence of overuse injuries before PHV 2. Players who had their PHV at an older age had a higher incidence of overuse injuries during PHV	1. U = 49.50 $r = 0.40$ $p < 0.05$ 2. U = 50.5 $r = 0.35$ $p < 0.05$	All other comparisons did not demonstrate significant differences	26 youth male soccer players were followed over 3 years around Peak Height Velocity (39 traumatic and 28 overuse injuries were recorded)	
Bult et al. [43]	- Maturity timing (PHV)	1. The injury incidence density (IID) in PHV period 4+5 (6 months after PHV) was significantly higher 2. The IID in PHV period 1 was significantly lower	1. IR = 1.31 95% CI 1.00 to 1.71 2. IR = 0.77 95% CI 0.62 to 0.95	- The IDD for PHV periods 2,3 and 6 were not significantly different when compared with the overall mean	170 players were monitored over 3 seasons (393 acute and 135 overuse injuries were recorded)	
Johnson et al. [46]	- Maturity status • Early-maturer • On-time • Late-maturer			- The analysis showed that the injury incidents did not differ significantly between categories of maturity status when adjusted for playing time, mean training time, mean height and position played	292 schoolboy players were followed over six years (476 injuries were registered across all the age groups)	
Bastos et al. [45]	- Age - Weight - Height - Body Mass - Duration of training	1. Players taller than 1.67 m reported more injuries than those with 1.66 m 2. Players with more than five years of training reported more injuries than those with less than five years of training	1. $p = 0.01$ 2. $p = 0.003$	- Age - Weight - Body Mass	301 athletes were involved in the study	BIOLOGICAL AND ANTHROPOMETRIC FACTORS
Rommers et al. [87]	- Growth velocity (cm/y)	1. Growth velocity on injury occurrence demonstrated a 15% increase in injury risk per cm of growth per year	1. OR = 1.15 95%CI: 1.05–1.26 $p = 0.003$		378 male players were involved in the study (105 injuries were recorded)	
Watson et al. [55]	- Age - Body mass - Soccer experience - VO _{2max} ml/kg/min	1. VO _{2max} ml/kg/min	1. OR = 0.94 95% CI 0.90 to 0.98 $p = 0.009$	- Age - Body mass - Soccer experience	54 female adolescent players were followed over 20-week (28 injuries and 38 illnesses were recorded)	

TABLE 2. Continue.

STUDY	RISK FACTORS EXAMINED	SIGNIFICANT RISK FACTOR IDENTIFIED	STATISTICAL RESULTS	NON-SIGNIFICANT RISK FACTORS	SAMPLE SIZE AND INJURY RATE	MAIN TOPIC AREA
Hägglund, & Waldén [58]	- Age - Relative age - BMI - Menarche - Previous acute knee injury - Current knee complaints - Familial disposition ACL injury - Training session per week - Match exposure ratio - Match with another team - Artificial turf exposure	1. Age > 14 years 2. Current knee complaints 3. Familial disposition ACL injury	1. HR = 1.82 95% CI 1.13 to 2.92 $p = 0.014$ 2. HR = 2.06 95% CI 1.30 to 3.26 $p = 0.002$ 3. HR = 1.87 95% CI 1.15 to 3.03 $p = 0.012$	- Relative age - BMI - Menarche - Previous acute knee injury - Training session per week - Match exposure ratio - Match with another team - Artificial turf exposure	4556 young players were studied (96 acute knee injuries were recorded, 21 of them ACL injuries)	
Rössler <i>et al.</i> [59]	- Age - Sex - Body height percentile category - Body mass percentile category - BMI percentile category - Match-training ratio - Playing position - Foot preferred - Playing surface	1. Body height percentile category (acute injuries) 2. Body height percentile category (overuse injuries) 3. Match training ratio (Match injuries) 4. Left foot preferred (Training injuries) 5. Artificial turf 6. Indoor	1. HR = 1.16 95% CI 1.02 to 1.32 $p = 0.019$ 2. HR = 1.21 95% CI 1.03 to 1.42 $p = 0.026$ 3. HR = 0.32 95% CI 0.23 to 0.46 $p < 0.001$ 4. HR = 1.53 95% CI 1.07 to 2.19 $p < 0.021$ 5. RR = 1.39 95% CI 1.12 to 1.73 $p < 0.001$ 6. RR = 0.68 95% CI 0.52 to 0.88 $p < 0.001$	- Age - Sex - Body mass percentile category - BMI percentile category - Playing position	A total of 6038 players were followed through one season (417 injuries occurred)	
Sugimoto <i>et al.</i> [57]	- Age - Height - Weight - BMI - Playing position - Hours of training per week - Seasons participated - Muscular strength - Joint laxity - Previous injuries	1. Age 2. Weight 3. BMI	1. OR = 1.602 95% CI 1.165 to 2.202 $p = 0.004$ 2. OR = 0.908 95% CI 0.834 to 0.989 $p = 0.026$ 3. OR = 1.430 95% CI 1.074 to 1.904 $p = 0.014$	- Height - Playing position - Hours of training per week - Seasons participated - Muscular strength - Joint laxity - Previous injuries	160 young female soccer players participated in the study	
Froholdt <i>et al.</i> [50]	- Sex - Age	1. Age (older players showed higher injury incidence)	1. RR = 1.7 95% CI 1.3 to 2.2	- Sex	159 were followed throughout 1 season (200 injuries were recorded)	
Van der Sluis <i>et al.</i> [66]	- Maturity timing (PHV) • Pre-PHV • PHV • Post-PHV	1. PHV versus Pre-PHV (traumatic injuries)	1. $d = 0.50$ $p = 0.006$	- The other comparisons did not show any significant difference	26 young soccer players were monitored over 3 years (178 injuries were recorded)	
Soligard <i>et al.</i> [26]	- Soccer skills: • Technical (ball receiving, passing and shooting, heading, dribbling, tackling) • Tactical (decision-making in ball possession, decision-making not in ball possession, decision-making in defense) • Physiological (endurance, speed/agility, strength, coordination/balance)	Data refer to impact of injury risk factors on overall injuries: 1. Ball receiving 2. Passing and shooting 3. Heading 4. Tackling 5. Decision-making when in ball possession 6. Decision-making when in defence 7. Strength	1. RR = 1.55 95% CI 1.04 to 2.31 2. RR = 1.82 95% CI 1.26 to 2.63 3. RR = 1.50 95% CI 1.13 to 2.00 4. RR = 1.70 95% CI 1.18 to 2.45 5. RR = 1.62 95% CI 1.08 to 2.45 6. RR = 1.81 95% CI 1.23 to 2.65 7. RR = 1.62 95% CI 1.18 to 2.22	- Dribbling - Decision-making when not in ball possession - Endurance - Speed/agility - Coordination/balance	1034 were included in the study (259 injuries were recorded)	TECHNICAL AND TACTICAL SKILLS

TABLE 2. Continue.

STUDY	RISK FACTORS EXAMINED	SIGNIFICANT RISK FACTOR IDENTIFIED	STATISTICAL RESULTS	NON-SIGNIFICANT RISK FACTORS	SAMPLE SIZE AND INJURY RATE	MAIN TOPIC AREA
Venturelli et al. [7]	- Age-category - Field position - Height - Body Mass - BMI - Yo-yo test - Squat jump (SJ) - Countermovement jump (CMJ) - Percentage difference between the two types of jumps (ΔJH) - Sit and reach score - Previous thigh strain injuries	1. Previous injuries 2. ΔJH 3. Height	1. HR = 2.80 CI 95% 1.19 to 6.54 2. HR = 0.79 CI 95% 0.71 to 0.87 3. HR = 1.17 CI 95% 1.06 to 1.25	- Age-category - Field position - Body Mass - BMI - Yo-yo test - Squat jump (SJ) - Countermovement jump (CMJ) - Sit and reach score	96 players were followed during an entire season (27 muscular strain were recorded)	PREVIOUS INJURIES
Emery et al. [33]	- Age - Previous injury, past 6 week - Previous injury, past 1 year - Height - Weight - Body mass index - Vertical jump - Predicted VO2max - Eyes closed dynamic balance	1. Female U14 age group 2. Male U14 age group 3. Previous injury, past 1 year	1. RR = 3.13 95% CI 1.14 to 10.67 $p < 0.05$ 2. RR = 2.45 95% CI 0.95 to 7.05 $p < 0.05$ 3. RR = 1.74 95% CI 1.0 to 3.1 $p < 0.05$	- Height - Weight - Body mass index - Vertical jump - Predicted VO2max - Eyes closed dynamic balance	344 were monitored for 13 weeks (78 injuries were reported)	
Clausen et al. [63]	- Previous knee injury - Knee injury and osteoarthritis outcome score (KOOS): • function in daily living (ADL) subscale • Pain subscale • Function in sport and recreation subscale (Sport/Recreation) • Knee-related quality of life subscale (QOL) • Other symptoms subscale	1. Previous knee injury 2. ADL score less than 80 points 3. Sport/recreation score less than 80 points 4. QOL score less than 80 points	1. RR = 3.64 95% CI 1.73 to 7.66 $p < 0.001$ 2. RR = 5.00 95% CI 1.53 to 16.38 $p < 0.001$ 3. RR = 2.23 95% CI 1.01 to 4.91 $p < 0.001$ 4. RR = 3.01 95% CI 1.13 to 8.00 $p < 0.001$	- Pain subscale - Other symptoms subscale	326 young soccer players were included in the study (34 knee injuries were recorded)	
Kucera et al. [41]	- One previous injury - Two or more previous injuries	1. One previous injury 2. Two or more previous injuries	1. RR = 2.57 95% CI 2.00 to 3.29 2. RR = 2.97 95% CI 2.28 to 3.86		1483 soccer players were monitored over 3 seasons	
Steffen et al. [62]	- Age - Height - Weight - Body mass index - Weekly sports participation - Previous injury - Previous ankle injury - Previous knee injury - Previous thigh injury - Previous groin injury - Years of organized soccer play	1. Previous injury 2. Previous ankle injury 3. Previous knee injury 4. Previous groin injury 5. Years of organized soccer play	1. OR = 1.9 95% CI 1.4 to 2.5 $p < 0.001$ 2. RR = 1.2 95% CI 1.1 to 1.3 $p < 0.001$ 3. RR = 1.4 95% CI 1.2 to 1.6 $p < 0.001$ 4. RR = 1.6 95% CI 1.2 to 2.1 $p = 0.004$ 5. RR = 1.12 95% CI 1.04 to 1.22 $p = 0.003$	- Age - Height - Weight - Body mass index - Weekly sports participation - Previous thigh injury	1430 players were included in the study	PREVIOUS INJURIES
Kofotolis [24]	- Previous injury - Age - Body mass - Height - Years of training	1. History of previous ankle sprain was a predictor variable in the under 15 age group 2. There was an increased risk of injury for the U15 group versus U12 groups	1. RR = 1.69 95% CI 1.0 to 2.9 2. RR = 2.34 95% CI 1.28 to 5.02	- Body mass - Height - Years of training	677 players were monitored for one season (211 were recorded and specifically 38 ankle injuries)	

TABLE 2. Continue.

STUDY	RISK FACTORS EXAMINED	SIGNIFICANT RISK FACTOR IDENTIFIED	STATISTICAL RESULTS	NON-SIGNIFICANT RISK FACTORS	SAMPLE SIZE AND INJURY RATE	MAIN TOPIC AREA
Aoki et al. [39]	- Age - Height - Weight - Playing turf	1. Low back pain showed a significantly higher incidence in the artificial grass versus the natural grass	1. IRR = 1.62 95% CI 1.06 to 2.48 $p < 0.05$	- Older taller, and late adolescent players had a significantly lower incidence of chronic pain	301 players participated to the study (256 injuries were registered on natural turf, 169 on artificial turf)	TURF TYPE AND EQUIPMENT
Haag et al. [56]	- Sex - Age - Previous injuries - Body mass index - Training experience - Playing surface - Position Weekly training load	1. Female vs Male 2. U19 vs U15 3. U17 vs U15 4. Previous spine injuries 5. Previous hip/groin injuries 6. Natural vs artificial turf 7. Goalkeeper vs midfielder	1. OR = 1.48 95% CI 1.05 to 2.08 $p = 0.019$ 2. OR = 1.84 95% CI 1.21 to 2.80 $p = 0.004$ 3. OR = 1.66 95% CI 1.19 to 2.31 $p = 0.003$ 4. OR = 1.74 95% CI 1.21 to 2.52 $p = 0.003$ 5. OR = 1.40 95% CI 1.02 to 1.93 $p = 0.039$ 6. OR = 1.56 95% CI 1.15 to 2.10 $p = 0.004$ 7. OR = 1.70 95% CI 1.04 to 2.78 $p = 0.036$	- Body mass index - Training experience Weekly training load	1110 soccer players were included in the study	
Emery & Meeuwisse [60]	- Age - Sex - Playing turf Playing level	1. U14 versus U18 (outdoor turf) 2. Outdoor versus indoor (Division 1) 3. Division 1 versus division 3–4 (outdoor) 4. Division 2 versus division 3–4 (outdoor)	1. RR = 2.73 95% CI 1.39 to 5.77 2. RR = 3.22 95% CI 1.8 to 6.12 3. RR = 5.4 95% CI 3.1 to 9.91 4. RR = 2.13 95% CI 0.53 to 5.37	- Sex - Division 1 versus division 3–4 (indoor) Division 2 versus division 3–4 (indoor)	233 players took part in the study and 142 players participated to the indoor comparison study (35 injuries were reported during indoor season and 78 injuries during outdoor season)	
O'Kane et al. [65]	- Pre-menarche versus post-menarche status - Type of field turf - Type of shoes Playing position	1. Grass field 2. Wear cleats on grass versus wear cleats on artificial turf 3. Defender versus forward	1. OR = 2.83 95% CI 1.49 to 5.31 2. OR = 2.40 9% CI 1.03 to 5.96 3. OR = 1.89 95% CI 1.03 to 4.317	- Pre-menarche versus post-menarche status - Wet surface	351 young female soccer players were followed over 4 seasons (173 acute lower extremity injuries were reported)	TURF TYPE AND EQUIPMENT

TABLE 2. Continue.

STUDY	RISK FACTORS EXAMINED	SIGNIFICANT RISK FACTOR IDENTIFIED	STATISTICAL RESULTS	NON-SIGNIFICANT RISK FACTORS	SAMPLE SIZE AND INJURY RATE	MAIN TOPIC AREA
Bowen et al. [21]	- Cumulative workloads (1, 2, 3 and 4 weekly) and acute:chronic (A:C) workload ratios: • Total distance (TD) • High-speed distance (HSD) • Accelerations (ACC) Training load (TL)	1. High total distance (TD; 112244–143918 m) over 4 weeks (overall injuries)	1. RR = 1.64 95% CI 1.05 to 2.58 $p = 0.031$	- TD above 143918 m - Low (0–8812 m) TD reduced the risk of overall and non-contact injury - Low 1-weekly HSD (0–756 m) significantly reduced overall and non-contact injury - A low amount of ACC over 3 weeks (744–2861) reduced non-contact and overall injury risk - A low 1-weekly TL (0–130 AU) significantly reduced overall and non-contact injuries - Low chronic TD (< 22335 m) with low A:C TD (0–0.32) reduced overall injury risk - A low ratio (0–0.36) for all chronic HSD significantly reduced the overall injury risk Low A:C ACC (0–0.33) with low chronic accelerations (< 1856) reduced overall injury risk	32 players were monitored through 2 seasons (138 injuries were recorded). 6.9/1000 hours of non-contact injuries 5.2/1000 hours of contact injuries)	TURF TYPE AND EQUIPMENT
		2. Moderate-high 4-weekly high-speed distance (HSD; 3502–5123 m) (non-contact injuries)	2. RR = 2.14 95% CI 1.31 to 3.50 $p = 0.003$			
		3. Moderate-high 1-weekly HSD (856–1449 m) (overall injuries)	3. RR = 1.73 95% CI 1.06 to 2.84 $p = 0.029$			
		4. Accelerations (ACC; ≥ 9254) performed in 3 weeks (overall and non-contact injuries)	4. RR = 3.84 95% CI 1.57 to 9.41 $p = 0.003$			
		5. High 1-weekly load (TL; 474–648 AU) (overall and non-contact injuries)	RR = 5.11 95% CI 1.75 to 14.96 $p = 0.003$			
		6. Very high 1-weekly TL (≥ 648 AU) (contact injury)	5. RR = 1.65 95% CI 1.04 to 2.62 $p = 0.032$			
		7. A:C TD (≥ 1.76) (contact injury)	RR = 2.20 95% CI 1.25 to 3.9 $p = 0.007$			
		8. Low chronic HSD (< 938 m) and high A:C HSD (1.41–1.96) (non-contact injuries)	6. RR = 4.84 95% CI 1.26 to 18.55 $p = 0.022$			
		9. High chronic HSD (> 938 m) and moderate-high A:C HSD (0.91–1.34) (non-contact injuries)	7. RR = 4.98 95% CI 1.31 to 19.02 $p = 0.019$			
		10. A:C ACC ratio very high (1.77) (contact injuries)	8. RR = 2.55 95% CI 1.15 to 5.68 $p = 0.022$			
		11. Moderate-high A:C TL (0.88–1.32) (non-contact injuries)	9. RR = 2.09 95% CI 1.06 to 4.12 $p = 0.033$			
		12. Moderate-low A:C TL (0.44–0.88) (contact injuries)	10. RR = 4.98 95% CI 1.30 to 18.99 $p = 0.019$			
Bell et al. [67]	- Sport specialization Volume of training per year	1. High sport specialization (Overuse knee injury)	1. OR = 2.05 95% CI 1.07 to 3.90 $p = 0.03$	- Moderate sport specialization Volume of training > 8 months (Acute knee injury)	761 young soccer athletes were included in the study	
		2. High sport specialization (Acute knee injury)	2. OR = 1.68 95% CI 1.01 to 2.78 $p = 0.046$			
		3. Volume of training > 8 months (Overuse knee injury)	3. OR = 1.97 95% CI 1.01 to 3.86 $p = 0.048$			
Frome et al. [68]	- Age - Sport specialization - Training ratio between weekly hours in organized sports and weekly hours in recreational free play	1. Age	1. OR = 1.10 95% CI 1.04 to 1.16 $p < 0.01$	- Specialized soccer athletes had decreased odds of reporting at least one previous injury compared with non-specialized athletes and similar odds of reporting at least one previous lower extremity overuse injury	2099 elite male youth soccer players were included in the study	EXTERNAL WORKLOAD AND SPORT SPECIALIZATION
		2. Sport specialization (severity)	2. IQR = 2–4 $p = 0.0003$			
		3. Training ratio > 2	3. OR = 1.35 95% CI 1.15 to 1.59 $p = 0.0003$			
Bacon & Mauger [54]	- Total distance (TD) • High-speed running meters (HSR)			- Total distance (TD) - High speed running meters (HSR)	41 youth soccer players were followed over 2 seasons (85 overuse injuries were recorded)	

b = effects; CI = confidence interval; d = Cohen's d effect size; ES = effect size; HR = hazard ratio; IQR = interquartile range; IR = injury risk; IRR = injury rate ratios; OR = odds ratio; P = significance level; r = Pearson correlation; RR = relative risk.

Clausen et al. [63] identified the KOOS questionnaire, composed of different subscales (function in daily living, pain subscale, function in sport and recreation, knee-related quality of life subscale, other symptoms) as a sensitive tool to identify players who were more prone to injuries. One study [64] analysed the impact of psychological factors on injuries. The authors found high levels of perceived life stress, high levels of perceived mastery climate, and high levels of life event to be psychological risk factors.

Biological risk factors

Within this section, we grouped injury risk factors related to chronological age [7, 20, 24, 33, 34, 39, 45, 50, 55–60, 62, 68, 80], biological age [20, 23, 35, 38, 43, 46, 66, 86], sex [33, 50, 56, 59, 60] and menarche status [48, 58, 65].

Ten studies [20, 24, 50, 56–58, 68, 80, 81, 85] identified advanced chronological age as an injury risk factor, whereas seven studies [7, 34, 45, 55, 59, 62, 64] did not find significant differences, while the remaining articles [33, 39, 60] reported a higher risk in younger soccer players.

Seven studies [28, 35, 38, 43, 46, 66, 86] investigated injury risk according to biological maturity. Most of these studies applied the Mirwald et al. [89] algorithm to assess the peak height velocity (PHV) used as an indicator of maturity timing. Only three studies [28, 46, 86] determined skeletal age using hand-wrist radiographs. Two studies [35, 66] found a higher injury risk during the PHV time compared to the period before the PHV, while Van der Sluis et al. [38] identified at-risk players as those who presented their PHV at an older age. Bult et al. [43] detected the six months after the PHV as more critical for injury risk. Among the studies assessing skeletal age, Johnson et al. [46] and Materne et al. [86] adopted the Fels method, while Le Gall et al. [28] used the Greulich–Pyle method. Le Gall et al. [28] found a higher incidence of tendinopathies, groin strains, and re-injuries in early-maturing players. Similarly, Materne et al. [86] identified a significantly greater risk of injury in early-maturing players compared with normal and mature players. In contrast, Johnson et al. [46], did not identify significant differences according to skeletal age when mean playing time, mean training time, mean height, and position played were considered in the analysis. Read et al. [23] assessed PHV only to analyse how biological maturity affects neuromuscular control. The authors observed higher landing forces on the left leg in players during PHV and lower knee valgus in players after the PHV period. Likewise, three studies [48, 58, 65] investigated the impact of menarche status on neuromuscular control in young female soccer players. O’Kane et al. [48] identified post-menarche status as a risk factor, while the remaining studies [58, 65] did not find significant differences between pre-menarche and post-menarche status.

Regarding sex differences, one study [56] found a higher injury risk in young female soccer players, whilst four studies [33, 50, 59, 60] did not identify any significant difference.

Anthropometric risk factors

Seventeen studies [7, 24, 25, 33, 34, 39, 45, 55–59, 62, 64, 72, 83, 87] discussed anthropometric risk factors.

Most studies did not identify height [24, 33, 34, 57, 62, 64] or body mass [7, 24, 33, 34, 45, 55, 59, 62, 64] as risk factors. Likewise, body mass index was not associated with injuries in young soccer players [7, 33, 34, 45, 56, 58, 59, 62, 64].

However, Venturelli et al. [7] found an association between height and muscular strains. Moreover, Bastos et al. [45] and Rössler et al. [59] observed that taller players reported more injuries than shorter ones. Kemper et al. [25] investigated the monthly changes in height and body mass index. The authors found that growth rates of at least 0.6 cm/month, monthly BMI-increase of $> 0.3 \text{ kg/m}^2$ and decrease in BMI value of at least 0.4 kg/m^2 were potential risk factors. Similarly, Rommers et al. [87] found a 15% increase in injury risk per cm of growth per year. Moreover, Rommers et al. [83] identified a greater increase in leg length (cm/year) as an overuse injury risk factor in young soccer players. One study [72] examined hamstring length without finding an association with injuries.

Only two articles [57, 83] reported weight and body mass index as injury risk factors.

Previous injuries

Eleven studies [7, 24, 27, 33, 41, 56–58, 62–64] analysed previous injuries as an intrinsic risk factor.

Most of them [7, 24, 33, 41, 56, 62–64] found a strong association between injury history and the risk of new injuries. Moreover, Kucera et al. [41] showed that the risk increased in players with two or more previous injuries ($RR = 2.97$) compared to players with one previous injury ($IRR = 2.57$). One study [58], even though not identifying an association between previous injuries and new injuries, found a familiar disposition to ACL injury as a risk factor.

Two studies [27, 57] did not identify injury history as an intrinsic risk factor.

Technical and tactical skills

Only two studies [26, 29] investigated the impact of technical and tactical skills on the risk of injury. Both these studies agreed that skilled players have a higher risk of injury. Particularly, Soligard et al. [26] observed that players with good ball-receiving, highly skilled in passing, shooting, heading, tackling, and dribbling were exposed to a higher risk of injuries. The authors assessed tactical abilities as well, and they observed that players who made good decisions when in ball possession and in defence incurred a significantly higher risk of injuries.

Schweibel et al. [29] also confirmed that skilled players were at higher risk of injuries. However, even less experienced players presented a greater predisposition to be injured.

Extrinsic risk factors

Extrinsic risk factors are defined as factors that are outside the body, irrespective of the injured players, and closely linked to the type of activity practised [88]. A total of seventeen articles [19, 21, 24, 39, 44, 45, 54, 56–60, 62, 64, 65, 67, 68] investigated injury extrinsic risk factors.

Turf type and equipment

Seven studies [19, 39, 56, 58–60, 65] reported the impact of the type of turf on injuries. Haag et al. [56], as well as O'Kane et al. [65] found a higher injury risk playing on natural turf than artificial turf. Conversely, Rössler et al. [59] observed a higher predisposition to injury playing on artificial turf (RR = 1.39). Similarly, Aoki et al. [39] reported a higher incidence of low back pain in players who trained on artificial grass. On the other hand, Emery & Meeuwiss [60] recorded a higher incidence of injuries in outdoor turf compared to indoor turf (RR = 3.22). One study [58] did not find significant differences between artificial turf and natural grass.

One study [19] prospectively investigated injury incidence in young soccer players who played on artificial turf, but without a direct comparison with injuries that occurred on natural grass.

Moreover, one study [65] examined the impact of the type of shoes on injury risk. The authors found that wearing cleats on grass produces a higher risk of injuries compared to cleats worn on artificial turf (OR = 2.40).

Instead, Lukášek & Kalichová [44] investigated the head acceleration during impact with the ball.

External workload

Seven articles [21, 54, 57–59, 62, 67] studied the association between external workload and injuries in young soccer players. Two studies [21, 54] prospectively collected GPS data, relating them to injury incidence. Bowen et al. [21] analysed the cumulative workload and the acute:chronic (A:C) workload ratio of total distance (TD), high-speed distance (HSD), and accelerations (ACC). These authors found that a high cumulative workload in 1 and 4 weeks, and a high A:C ACC, were associated with a greater injury risk, as reported in Table 2. Likewise, Bacon & Mauger [54] identified an association close to significant levels between the total distance and high speed running cumulative load of 2 weeks with overuse injuries. Three studies [57, 58, 62] evaluated weekly training exposure, but the authors did not identify hours of training per week or training sessions per week as risk factors. Bell et al. [67], however, observed that an annual training volume greater than 8 months produced a higher risk of overuse knee injuries. Rössler et al. [59] investigated the match-training ratio, observing that adolescent players who had more training exposure suffered from fewer match injuries. Indeed, non-injured players presented a match-training ratio of 1:7, unlike injured players, who had a match-training ratio of 1:5.

Playing position and sport specialization

Several studies [24, 56, 57, 59, 65] investigated how different playing positions may elicit different injury risks. Kofotolis [24] reported a higher injury rate in goalkeepers compared with forwards and defenders. Similarly, Haag et al. [56] found a higher risk of injury in goalkeepers compared to midfielders (OR = 1.56). Meanwhile, O'Kane et al. [65] observed that defenders were more exposed to injury risk compared with forwards (OR = 1.89). On the other hand, two studies [57, 59] did not identify playing position as a risk factor. Moreover, Sugimoto et al. [57] observed that players who experienced multiple playing positions reported a history of injuries with fewer musculoskeletal strains compared to single-position players.

Regarding this topic, sport specialization, defined as intense practice in one sport while excluding others [90], was investigated in seven articles [24, 45, 56, 62, 64, 67, 68]. Bastos et al. [45] found that players with more than five years of training were more prone to injuries compared to players with less than five years of training. Steffen et al. [62, 64] obtained similar results. The authors found that the risk of injury rose with increasing years of organised soccer play. Consistently with these results, Bell et al. [67] noted that highly specialised athletes reported more overuse and acute knee injuries. However, Frome et al. [68] did not find an association between sport specialization and risk of injury; also Kofotolis [24] and Haag et al. [56] did not identify the number of years of training as an injury risk factor.

DISCUSSION

The aim of this review was to develop an overall point of view of the potential risk factors in young soccer players and to discuss how these factors could interact and determine the injury onset.

Different intrinsic (neuromuscular control, chronological age, biological age, sex, previous injuries, technical and tactical skills) and extrinsic (turf type, external workload, playing position, and sport specialization) injury risk factors were identified and discussed in the subsequent sections.

The identification of injury risk factors represents the step immediately preceding the implementation of prevention strategies [13]. This process is crucial in young soccer players to promote proper talent development, but at the same time, it is extremely complex. Indeed, injury is a multifactorial phenomenon determined by the interaction of numerous elements. These elements are represented by the injury risk factors, which interacting with each other result in a “web of determinants” generating unpredictable and unplanned relations [91]. According to the Meeuwisse's dynamic model [14], the combination of these factors (intrinsic and extrinsic) makes athletes prone to injury. However, all these factors together represent the necessary but not sufficient condition for causing an injury, because the presence of an inciting event (e.g. match schedule, playing situation, joint motion) is the real factor that determines the onset of the injuries [92].

Faced with a complex phenomenon such as injury, many authors used a reductionist approach, which allows analysis of the various risk factors separately [91]. This approach is useful in simplifying the interpretation of the phenomenon, but does not allow the analysis of how the interaction of different factors may determine the onset of injuries.

Intrinsic risk factors

Several intrinsic risk factors were identified in the current review: neuromuscular control, physiological and psychological factors, biological and anthropometric factors, previous injuries, technical and tactical skills.

Almost half of the articles selected in this review investigated the link between alteration in neuromuscular control and injury risk. Neuromuscular control is defined as the unconscious response of a muscle to a stimulus to ensure dynamic joint stability [93]. This means that a deficit in the neuromuscular control may produce excessive joint stress [94] leading consequently to an injury. Different screening tests were adopted in the scientific literature to detect neuromuscular dysfunction. Ko *et al.* [34] identified an association between a low score in the star excursion balance test (SEBT) and risk of ankle sprain.

Four studies investigated [47, 47, 61, 82] knee control during a motor task. Räisänen *et al.* [47] did not find an association between the FKPA during single-leg squat and injuries, while O’Kane *et al.* [48, 61] identified knee valgus as an intrinsic risk factor. The conflicting results may be explained by the different evaluation methods (FKPA vs NKS) and different motor tasks (single-leg squat vs drop-jump test) used. However, knee valgus seems to be a risk factor only in female postmenarchal players [48], confirming the idea that an injury is determined by the interaction of different factors. Puberty is a critical period for young athletes, characterised by rapid changes in stature, limb flexibility, strength and in hormonal profile [95]. Indeed, Nguyen *et al.* [49], investigating longitudinal changes in hip strength and range of motion in female youth soccer players, found an increase in hip internal rotation and abduction with a contemporary decrease in external rotation and adduction. The changes in hip range of motion may alter the neuromuscular control, compromising muscular activation during dynamic activities, and consequently increasing lower extremities’ injury risk [49]. Moreover, the higher oestrogen concentration during the postmenarchal period may affect the ligament structures and explain the greater predisposition to knee injuries in female athletes [95]. Although some studies confirmed a higher injury predisposition during adolescence in female soccer players [56], puberty represents a sensitive time also in young male soccer players. A few studies [28, 46, 86] used hand-wrist radiographs to investigate the impact of maturity status on injury risk. Materne *et al.* [86] and Le Gall *et al.* [28] found a higher risk of injury in early-maturing players. Instead, the most common method to assess the maturity status was the Mirwald *et al.* [89] algorithm, performed to determine the peak height velocity (PHV) of

the young soccer players. Although the the maturity offset can present an error of ± 1 year 95% of the time [89], it is a very useful tool because it is not invasive. The period around PHV was identified as critical in the increase of injury risk [35, 43, 66]. During this phase, players experience rapid growth, and changes in muscle-tendon junctions, ligament, cartilage, and bone density [35]. This increase in the vulnerability of muscular tissues, associated with a concomitant rise in training load, may explain the higher injury incidence in the PHV phase. Furthermore, this stage has been defined as a period of “adolescent awkwardness” in which there is impairment in motor skill performance due to the onset of rapid growth processes [96]. In support of this hypothesis, Read *et al.* [23] found higher landing forces on the left leg in players during PHV and lowering of knee valgus in players after PHV. The findings of this study show that high landing forces may be associated with greater injury risk and may be due to the temporary decrease in motor skills [23].

During a soccer match, the neuromuscular control may also be altered by the players’ state of fatigue due to the increase in minutes of play. As proof of this, several studies [75, 76, 78, 79, 97–100] reported higher injury incidence during the second half of the match, in particular during the last 15 minutes. Different studies tried to replicate soccer-specific fatigue to investigate its effect on neuromuscular control. Lehnert *et al.* [30, 52] observed a decrease in absolute and relative leg stiffness after SAFT protocol execution, while De Ste Croix *et al.* [22] reported a longer electromechanical delay (EMD) in U13 soccer players. The impairment of these mechanisms may be dangerous for joint stability. Indeed, the reduction in leg stiffness is associated with greater ground contact time, changes in centre of mass displacement, and consequently less movement efficiency and increase in shear force absorption [52]. Likewise, a longer EMD reflects an alteration in muscle activation. However, the fatigue produced through the SAFT protocol seems to have no effects on isokinetic strength of the hamstrings and quadriceps [30], on hamstring/quadriceps ratio [30, 52], or on knee kinematics registered during a single leg drop jump and countermovement jump [71]. Meanwhile, Wollin *et al.* [51] investigated the effect of fatigue produced by a congested soccer match period. The authors found a transient reduction in hamstring strength and associated pain during hamstring maximum voluntary isometric contraction. These results highlight an incomplete recovery that may persist for up to 48 hours after a match and the need to monitor players’ physiological responses to avoid the risk of injuries.

All these studies investigated the effect of fatigue on physiological parameters in a short time period, *i.e.* after SAFT protocol execution [22, 30, 52, 71] or after a congested match period [51], without being able to study the association with the onset of the injuries. For this purpose, different studies [5, 31, 69] investigated prospectively the stress and fatigue state induced by training, and the link with injuries during one [31, 69] and two seasons [5]. Brink *et al.* [5], as well as Watson *et al.* [69], found an association between high internal training load (s-RPE) [5, 69], monotony, and strain [5] with

injuries and illness. These results highlight the need to monitor stress and recovery to identify young soccer players at risk of injuries and illnesses. Moreover, physical trainers and coaches should be aware of the importance of improving the physical fitness of the athletes needed to tolerate a high training load during the season. Indeed, Watson et al. [55] found that lower preseason aerobic fitness was associated with a higher risk of injuries and illness during the season. However, Raya-González et al. [31] did not find any association between weekly training load and risk of injury. This discrepancy may be explained by the small sample size and the small number of injuries found.

In addition to physiological responses, other authors [63, 64] considered it important to monitor the psychological sphere. Indeed, Steffen et al. [64] identified a high level of perceived life stress, high levels of perceived mastery climate and high levels of life event as injury risk factors. Therefore, coaches must be able to create a positive motivational atmosphere, reducing players' life stress perception. In fact, stress may increase muscle tension and impair motor control [101], causing a higher predisposition to injury.

Among the several intrinsic risk factors analysed, the anthropometric parameters were widely investigated. Most studies agree that neither height [24, 33, 34, 57, 62, 64] nor body mass [7, 24, 33, 34, 45, 55, 59, 62, 64] nor body mass index [7, 33, 34, 45, 56, 58, 59, 62, 64] is associated with higher injury risk. Rather, it was found that a rapid gain in height or body mass index represented an injury risk factor in itself [25, 83, 87]. These results confirm the problems, previously mentioned, related to the growth process that occurs around PHV. A few studies recognised stature as an injury risk factor [7, 45, 59]. In this case, the authors tried to explain these results through the higher biomechanical load [59] or the poor motor coordination [7] that characterizes taller players. However, while poor motor skills could be an injury risk factor [7, 96], two studies [26, 29] also identified highly skilled players to be at risk of injury. However, this should not be misunderstood. Indeed, the authors simply suggest that skilled players, with good technical and tactical abilities, are more involved in the game and consequently more exposed to tackles and duels. Therefore, high motor skills do not represent a direct risk factor, but rather expose athletes to contact and duels. For this reason, it is important to promote a fair-play policy and encourage proper rule enforcement and adherence [102, 103].

Aware of the several factors that may lead to an injury, it is important to have an overview of the risks connected with playing soccer, to promote prevention strategies and to reduce the onset of injuries. This is crucial, because an injury may represent in turn an intrinsic risk factor for new injuries. Many studies [7, 24, 27, 33, 41, 56, 62–64] investigated the association between injury history and new injuries.

Most of them [7, 24, 33, 41, 56, 62–64] found a strong relationship, with the risk increasing with the number of previous injuries [41].

Extrinsic risk factors

In the present review, turf type, equipment, external workload, playing position, and sport specialization were classified as extrinsic risk factors.

Several studies investigated the impact of the playing surface on the injury risk. The related results are controversial and difficult to interpret. Two studies [56, 65] found a higher injury risk playing on natural turf compared to artificial turf. Conversely, Rössler et al. [59] and Aoki et al. [39] reported a higher risk on artificial turf. Moreover, one study [58] did not find differences between the playing surfaces. A meta-analysis tried to clarify the discrepancy of the results [104]. The authors found a lower injury incidence rate playing on artificial turf. However, considering the heterogeneity of the studies included in the meta-analysis, it is difficult to reach an absolute conclusion. Even in the present review, the selected studies are characterised by different experimental designs. Moreover, we must consider the quality and generation of the fields employed in the studies. It often happens that young soccer players train on worn playing surfaces, unlike elite and adult soccer players [59]. In addition to the playing surface, the type of shoes may represent an extrinsic risk factor. Unfortunately, only one study [65] approached this issue. The authors observed that wearing cleats on grass was associated with a higher risk of injuries compared to wearing cleats on artificial turf.

Lukášek & Kalichová [44] stated that repeated head impacts with the ball may be dangerous in young soccer players, causing a functional problem in the brain. In light of this statement, recently the Scottish Football Association decided to ban heading for under 12 players. However, the article mentioned presents a low-quality score.

Even exposing athletes to high training volume may be dangerous [21, 54, 67]. As previously mentioned, young soccer players experience a period of rapid changes in muscle, tendon, and ligament structures, and a concomitant increase in the training volume may lead to a greater predisposition to injury. Bowen et al. [21] and Bacon & Mauger [54] observed that higher cumulative workload in total distance, high-speed distance, and accelerations was associated with greater injury risk. These results, according to the Kenttä & Hassmén [105] model, suggest that a higher workload, associated with poor recovery status, increases the risk of overuse injuries. In confirmation of this, Bell et al. [67] reported that playing or training in soccer for more than 8 months per year increased the risk of overuse injuries. This does not mean that it is wrong to promote intense training in young soccer players; a proper training stimulus increases physical tolerance and resilience to injury risk [21]. Indeed, Rössler et al. [59] observed that a greater weekly training volume had a protective effect on injuries. Rather, it is important to ensure adequate recovery and to avoid a sudden increase in the weekly workload, as suggested by Gabbet [106]. Moreover, coaches and trainers must be able to adapt the physical demands in relation to the individual differences (e.g., sex, age, maturity status). These physical demands may also change in

relation to playing position. Indeed, coaches and physical trainers should be aware that different playing positions elicit different physical efforts and different involvement in the game, and consequently different exposure to injury. O’Kane *et al.* [65] found higher injury risk in defenders, while Haag *et al.* [56] found higher injury risk in goalkeepers. It is difficult to reach a conclusion from these results, because different play styles and strategies, competitive levels and different skill levels may influence the risk of injury. In addition, Sugimoto *et al.* [57] observed that players who experienced multiple playing positions reported fewer musculoskeletal injuries compared to single-position players. We can speculate that experiencing different playing positions may increase adaptability to distinct tasks and improve technical and tactical skills. On the other hand, the specialization in a single playing position may subject athletes to the same repetitive movement and increase the risk of overuse injuries. This aspect is closely linked to the problem of early specialization in young athletes. Several studies [45, 62, 64, 67] reported an association between soccer specialization and injury risk. Moreover, other factors such as pressures placed on the athletes could lead to stress, lack of energy, sleep disturbances, and consequently burnout [107].

For this reason, it is important to promote multisport participation to avoid overuse injuries as well as to improve decision-making skills and mental health and to encourage social relationships with other peers.

STRENGTHS AND LIMITATIONS OF THE REVIEW

According to our knowledge, this is the first review that has tried to summarize the injury risk factors in young soccer players. However, there are several limitations to consider. As in our companion review (part I) [108], the heterogeneity of the studies, mainly due to different experimental designs and different injury risk investigated, did not allow us to perform statistics or meta-analysis of the results.

Several studies, classified as cross-sectional or quasi-experimental studies [22, 23, 30, 40], reported injury risk factors; however, the authors did not investigate the direct association with the onset of injuries. Therefore, the risk factors were included in the present review, but a longitudinal design is needed to confirm a possible association.

The injury risk factors were grouped into intrinsic and extrinsic risk factors; however, the use of different tests, collection processes, follow-up period, and the different injury types investigated (e.g., overuse, traumatic, non-contact) make comparison between studies difficult. Moreover, all the risk factors were discussed together in the present review, albeit collected on samples characterised by different age and sex. The publications are limited to English language, and relevant studies may have been excluded.

CONCLUSIONS

Injury is a complex and multifactorial phenomenon. A deep awareness of these factors is crucial to promote adequate prevention strategies. In the present review, injury risk factors were divided into intrinsic and extrinsic ones. Among the intrinsic risk factors, the following results have been reported:

- Proper neuromuscular control plays an important role in limiting the risk of injury. Indeed, limb asymmetry and knee valgus on landing were identified as relevant injury risk factors.
- Maturation processes may increase the injury risk in postmenarchal female players and in male soccer players during PHV.
- Physiological factors, such as fatigue and poor recovery, may contribute to the increase in injury risk.
- The results related to anthropometric characteristics (i.e., height and body mass) are still controversial.
- Previous injuries were recognised as important intrinsic factors.
- Other studies, investigating the impact of technical and tactical skills, identified highly skilled players as being at greater risk of injuries.

Among extrinsic risk factors, the following results have been reported:

- The results related to playing surface are controversial.
- An excessive weekly workload increased the risk of injuries. The risk could also be linked to the playing position, but the results analysed in the present review are unclear.
- Some authors found that sport specialization and a high annual volume of training increased the risk of overuse and acute injuries.

Future studies should aim to clarify how the injury risk changes in relation to chronological age, maturation, and sex. Moreover, it would be useful to develop a test battery to identify players at risk of injury. Considering the various factors linked to the onset of injuries, authors should promote longitudinal investigations with a complex system rather than a reductionist approach.

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The authors have declared that no conflicts/competing interests exist.

Contributorship

MM and AT was responsible for the conception and design of the study. MM, AT and AF conducted the literature review. MM, AT and MG contributed to data collection and interpretation. The article was written by MM and AT. All authors contributed to the reviewing of the manuscript.

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Body size, maturation and motor performance in young soccer players: relationship of technical actions in small-sided games

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ABSTRACT: The objective of this study was to investigate the relative contributions of body size, skeletal age, and motor performance variables with technical actions through an ecological model during small-sided soccer games, and the interaction of biological maturation with technical and motor performance in young players. In this cross-sectional study, eighty-two young players (14.4 ± 1.1 years), belonging to state-level soccer teams and divided by category (U-13 and U-15), were included. Players having an injury in the evaluation period were not included in the study. Measurements of body size, skeletal age (SA), motor tests, and technical actions in small-sided games (SSG) were performed (3×3 plus goalkeeper) in two periods (halves) of four minutes. Differences between age groups were found for SA ($ES = -2.36$), chronological age ($ES = -3.89$), body mass ($ES = -2.09$), height ($ES = -1.90$), and fat-free mass ($ES = -2.09$). Positive associations were found between body size ($R = 0.43$ to $R = 0.48$) and manipulation ($R = 0.50$ to $R = 0.52$) indicators and numbers of technical actions (CB and SS), except for stature with LB ($R = -0.42$) in the U-13 age group. In the U-15 category, skeletal age ($R = -0.29$ to $R = -0.30$) and body mass ($R = -0.28$ to $R = -0.29$) were negatively associated with the number of technical actions (RB, NB, LB, and OB) ($P > 0.05$) and positively with the balance with LB ($R = 0.26$). In conclusion, body size, SA, and motor performance influenced technical actions in SSG differentially in each category. U-13 heavier players and those with a better motor performance presented higher involvement due to the higher number of performed technical actions (receiving the ball, playing a neutral and playing an offensive ball) during SSG.

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INTRODUCTION

Adolescence is marked by great variability, especially in body size characteristics. This variability in adolescence is notorious at the initial stage of the long-term training process of young soccer players [1]. Such large differences among young players makes the issue of identifying and developing a talent a complex and very difficult task [2], mainly due to the well-known influence of maturation on the performance indicators of young soccer players [3, 4].

The profile of young soccer players differs from the general population at the same age group. In general, they have greater body size and strength [3–6]. Nevertheless, in practical settings, it is possible to observe the participation of some players with smaller body size, compared to their peers. Indeed, it is not unusual that smaller players and with lower skeletal age present worse performance in motor and specific skill tests, in particular, in tests related to speed and agility attributes [7]. Due to the presence of these inequalities in the sports environment, young soccer player with smaller body size and lower skeletal age tend to be excluded during the long-term training

process, mainly due to the influence of biological maturation at this stage of life [5, 6, 8].

However, excluding “smaller” players from the training process can be harmful to the team in the medium term, since at the end of adolescence, the physical advantages promoted by body size differences will no longer be significant [9]. Therefore, evaluating them through isolated soccer-specific skill tests might neglect technical qualities performed in real situations, since these batteries are usually influenced by functional capacities, overestimating advanced players in maturation processes [10], which brings the need for new methods such as the number of technical actions, helping professionals involved in the training and evaluation of young soccer players. In addition, the interaction between maturation and age may provide certain advantages for older soccer players in the selection and training process [11], especially when the biennial category division process is adopted; for example, differences between game categories have been observed when comparing body size, skeletal

age, and performance indicators in various batteries of specific skill tests [12, 13].

Although the results of several studies have demonstrated the physical advantages that maturation exerts on sport performance [5, 14], the influence of the body growth process on the number of technical actions performed by young soccer players during a soccer match still remains unclear, given that the majority of studies in this field have been mainly focused on the influence of biological maturation on the performance of isolated skill tests, therefore demonstrating low ecological validity [15], reflecting the absence of complex decision-making processes, and thus neglecting the systemic characteristics of soccer, which is influenced by constraints imposed by the individual, environment and task triad [16]. In this way, the evaluation of the number of technical actions during games, together with body growth, skeletal age and motor performance in an ecological context, can help in assessing the influence of the body growth process on the participation of players in the game, which in turn could be analysed due to a multivariate approach [17], therefore assisting training professionals in monitoring and selecting young soccer players [18].

In this context, small-sided soccer games (SSG) have been considered as training drills with the possibility of assessing technical performance [19], and have been proposed to be a viable tool for evaluation of the number of technical actions [1], contemplating technical, tactical and physical aspects of the soccer game [20], which is thought to promote stimuli similar to those found in official match situations [21].

Despite showing moderate variability in technical actions between training sessions, SSG have also been shown to be a reliable tool for systematic monitoring of technical performance in an ecological model, since they increase individual participation in the number of technical actions [22], mimicking the unpredictable feature of the game, requiring participants to adjust their movements according to individual, environmental and task dynamic constraints [16], and presenting high stability in technical performance across a 16-month training period in elite young soccer players [19].

Observing the performance of young players during SSG and assessing the influence of body growth and maturation on SSG performance could help coaching staff and practitioners working with the training of young soccer players in formulating better guidance that would assist planning, monitoring and developing players based on their size and motor characteristics. Based on previous information, our hypothesis was that there would be differences in the involvement (number of performed technical actions) of young soccer players in SSG due to body size differences and maturational status. Thus, the aim of this study was to evaluate the relative contributions of body size, skeletal age and motor performance variables on technical actions through an ecological model during small-sided soccer games, and the interaction of biological maturation and technical and motor performance in young players.

MATERIALS AND METHODS

Participants

Among the ninety-seven eligible young soccer players, the final sample was composed of eighty-five athletes, and their training was composed of 4–5 weekly sessions, with training session duration of 120–180 min, including soccer training sessions, small-sided games, and strength and conditioning training sessions, as previously described [23]. The study was conducted in accordance with the National Health Council resolution (466/2012) and was approved by the Research Ethics Committee of the local university (Proc. 2.650.232/2018). As inclusion criteria, it was required that the players belong to the youth academy team, not being in the pre-evaluation period in the club and not having any kind of injury during the evaluation period. Thus, data from 15 players who did not meet these criteria were removed from the final analysis [23].

Experimental design

In this cross-sectional study, data collection occurred between September and October 2018, just before the beginning of the teams' pre-season. Data collection occurred on four days (D1, D2, D3, and D4). On the first day (D1), anthropometric measurements and motor performance tests were conducted; on the second day (D2), body composition measurements were performed using the plethysmography method; on day three (D3), players had their wrists X-rayed; and on the last day (D4), SSG were performed (3 × 3). Athletes were instructed to recover 48 hours before the beginning of data collection and the recovery time was 21 hours between tests. All players were familiar with tests and experimental procedures.

Anthropometry and body composition

Body mass and height measurements were obtained, according to criteria described by Gordon, Chumlea and Roche [24]. Fat-free mass was estimated by the whole-body plethysmography method using the Body Composition System (BOD POD, Life Measurement Inc., Concord, CA, USA) estimated by body density based on the two-component model, using the specific equation of Siri [25] and adjusted by age-specific constants described by Lohman [26].

Chronological and skeletal age

To establish the chronological age (CA) in centesimal form, the difference between the date of birth of the player and the date of evaluation of the wrist and left-hand X-ray was calculated. Players were classified by category according to their year of birth; U-13 for those born in 2005 and 2006 and U-15 for those born in 2003 and 2004. Skeletal age was measured through anteroposterior X-ray of the left hand and wrist performed in a specialized laboratory; skeletal age (SA) was estimated by means of the TW3 method [27] by a single trained observer; the method uses individual skeletal age assignment for 13 hand and wrist bones through radiographs. Twenty radiographs (20%) were blindly assessed a second time after 15 days. The intra-



FIG. 1. Team composition according to the specific skill results.

class correlation coefficient found was 0.97 ($P < 0.01$) and intra-observer error was 0.26 years.

Small-sided games (SSG)

SSG in the 3 × 3 plus goalkeeper was used in this study [20, 28]. This format has been used for simulating the demands of the game and developing technical skills [29], in addition to being a tool for identifying/monitoring young talents [30]. SSG consisted of two periods (halves) of four minutes. Passive recovery of 1 min was allowed between halves. The pitch area adopted was 36 m (width) × 27 m (length) [20, 28]. All players were largely familiarized with this SSG format, as it was habitually used in their training routines. Each player participated in only one SSG.

Within each age group, teams were arranged based on two criteria: ranking in the specific battery skill results [23, 31, 32], and game position (Figure 1).

In the first confrontation, team A consisted of the best defender, best midfielder and best forward, while team B consisted of the second-best defender, second-best midfielder and second-best forward. This counterbalanced procedure was adopted to allow similar technical performance conditions between teams.

Technical actions in SSG

The number of technical actions was adopted as an indicator of technical performance [33]. The number of technical actions was recorded during SSG using a camera (Casio EX-10, 30 Hz frequency acquisition, São Paulo - Brazil) located 6 m above and to one side of the pitch long axis at a distance of 15 m from the pitch. The Lince software was used to code SSG technical actions. According to the specific taxonomy from the observational methodology, this study can be classified as nomothetic, punctual and multidimensional [34]. The following technical actions were recorded: conquering the ball (CB), receiving the ball (RB), playing a neutral ball (NB), losing the ball (LB), playing an offensive ball (OB), and successful goal attempts (SS). The procedures adopted for each of the technical actions were described in a previous study [23]. This tool has validity of 0.74 [35].

Twenty young soccer players (20%) were blindly re-evaluated a second time after 15 days. The intraclass correlation coefficient found for CB was 0.83 ($P < 0.01$), for RB 0.96 ($P < 0.01$), for NB 0.97 ($P < 0.01$), for LB 0.96 ($P < 0.01$), for OB 0.98 ($P < 0.01$) and for SS 0.96 ($P < 0.01$).

Motor performance

To evaluate motor performance, a battery of tests proposed by Luz et al. [36] was adopted, using six tests to evaluate locomotion, balance, and manipulation. This battery has very good validity for this population ($X^2 = 12.04$, $p = 0.061$; NFL = 0.982; CFI = 0.991; RMSEA = 0.059). For locomotion, the shuttle run and long jump tests were applied. In the shuttle run test, the player runs from one line to another separated by 10 m and picks up two wooden blocks, one at a time; when running back, the athlete must place the block beyond the starting line. The final result of the test was the time spent on the course; the test was applied twice and only the best time obtained was considered. In the long jump, the athlete jumped from one line with both feet simultaneously. The player repeated the test twice, and the greatest distance (in metres) between the start line and the back of the heel on landing closest to the start line was used as the final result. To evaluate balance, the platform displacement and lateral jump tests were performed. On the lateral displacement platform, the player walked laterally using two wooden platforms (25 cm × 25 cm × 2 cm) for 20 seconds. For each successful transfer between platforms, two points were scored, one for each platform; the test was applied twice and only the best result was used. In the side jump, the athlete jumped laterally with both feet together over a five cm beam as fast as possible for 15 seconds. For each successful jump, one point was scored; the test was applied twice and only the best result was used. For manipulation, throwing speed and kicking speed tests were performed. In the throwing speed test, the player throws a baseball at maximum speed against a wall. Two attempts were made, and the final result was the highest speed throw. For the kick speed, kicks were performed at maximum speed against a wall with the player's preferred leg. Two attempts were

made and the final result was the kick with the highest speed. Subjects were familiarized with tests through an attempt prior to evaluation. 2D analysis, kicks, and throws were recorded by a camera, model Casio EX-10 (Cassio, São Paulo, Brazil), at an adjusted rate of 240 Hz and laterally positioned at a distance of 5 m from the central test area to allow observation of the ball trajectory. The area where subjects performed the tasks was calibrated using four metal rods, in an area of $2.0 \times 1.6 \text{ m}^2$, with eight known Cartesian coordinate points [37].

For calculation of the throwing and kicking speed, 2D images were reconstructed using the Dvideo Software [38]. The first ten frames after the last favourite hand or foot lost contact with the ball were used for reconstruction. 2D distances covered by the ball were calculated in the Microsoft Excel software and estimated through calculation of the Euclidean distance and distance in metres per second (m/s).

The results of the six tests were transformed into a Z score for further analysis. To obtain the locomotion variable, the results of the shuttle run and long jump tests were added; for the balance variable, the results of the platform displacement test and lateral jump test were added; and for the manipulation variable, the results of the throwing speed and kicking speed tests were used. Twenty young soccer players (20%) were blindly re-evaluated a second time after 15 days. The intraclass correlation coefficient found for the shuttle run test was 0.84 ($P < 0.01$), for the long jump test, 0.93 ($P < 0.01$), for the platform displacement test, 0.78 ($P < 0.01$), for the lateral jump test, 0.94 ($P < 0.01$), for the throwing speed test, 0.92 ($P < 0.01$) and for the kicking speed test, 0.95 ($P < 0.01$).

Statistical analysis

Data are described as mean and 95% confidence interval. Data normality was evaluated by the asymmetry and kurtosis graph method, and variables that did not present normality were fitted by a logarithmic equation. The independent t test was used to compare U-13 and U-15 categories for body size, skeletal age, motor performance and technical actions and the effect size was observed by Hedges' g. Pearson's correlation coefficient was applied to evaluate the relationship between body size, skeletal age, and motor performance and technical actions by age group and only variables that showed $p < 0.05$ were added to the linear regression model. Finally, linear regression was adopted to assess the power of explanation between the variables motor performance, body size and skeletal age, and those of technical actions adjusted by motor performance, body size and skeletal age. The significance adopted was 5% and the software used was SPSS 24.0 (IBM Corp., Armonk, NY).

RESULTS

Table 1 describes the sample characteristics stratified by category (U-13 and U15), for technical actions, anthropometric and motor performance variables. Players had a mean chronological age of 14.4 ± 1.1 years. When comparing age groups, significant differences were found for all anthropometric variables. A higher SA value was observed for U-15 soccer players ($ES = -2.36$), who also had greater chronological age ($ES = -3.89$), body mass ($ES = -2.09$), height ($ES = -1.90$), and fat-free mass ($ES = -2.09$). Technical actions and motor performance variables did not show differences between categories.

TABLE 1. Body size, skeletal age, motor performance and SSG technical actions by category (mean and CI 95%)

Variables	Total Sample	U-13 (n = 24)	U-15 (n = 58)	t	P
Chronological age (years)	14.4 (14.1–14.6)	12.9 (12.6–13.1)	15.0 (14.9–15.1)	-16.191	< 0.001*
Skeletal age (years) [#]	14.7 (14.7–14.3)	13.0 (12.4–14.5)	15.4 (15.1–16.0)	-9.753	< 0.001*
Body mass (kg)	57.9 (55.6–60.2)	46.8 (42.9–50.6)	62.5 (60.7–64.2)	-8.698	< 0.001*
Stature (cm)	169.5 (167.3–171.8)	159.4 (155.1–163.6)	173.8 (172.1–175.5)	-7.884	< 0.001*
Fat free mass (kg)	51.7 (48.5–53.9)	41.0 (37.0–45.0)	56.2 (54.6–57.8)	-8.694	< 0.001*
Locomotion (score)	0.0 (-0.1–0.1)	0.0 (-0.2–0.2)	0.0 (-0.1–0.1)	-0.169	0.867
Balance (score)	0.0 (-0.2–0.2)	0.0 (-0.4–0.4)	0.0 (-0.2–0.2)	-0.002	0.999
Manipulation (score)	0.0 (-0.2–0.2)	0.0 (-0.3–0.3)	0.0 (-0.2–0.2)	-0.036	0.972
Conquering the ball (number of actions) [#]	1.9 (1.5–2.2)	2.1 (1.5–2.7)	1.8 (1.4–2.2)	0.657	0.513
Receiving the ball (number of actions)	10.6 (9.9–11.4)	10.9 (9.5–12.3)	10.5 (9.6–2.2)	0.421	0.675
Neutral ball (number of actions)	6.7 (6.1–7.4)	6.7 (5.4–8.0)	6.7 (6.0–7.6)	-0.068	0.946
Losing the ball (number of actions)	2.6 (2.3–3.0)	2.4 (1.8–3.2)	2.7 (2.3–3.2)	-0.630	0.530
Playing an offensive ball (number of actions)	1.9 (1.6–2.5)	1.6 (1.1–2.1)	2.0 (1.6–2.5)	-1.031	0.306
Executing a successful shot (number of actions) [#]	2.1 (1.7–2.4)	1.7 (1.1–2.3)	2.2 (1.8–2.7)	-0.543	0.591

Note: [#] = transformed data $\log^{10}$; * = significant difference between U-13 and U-15 category ($P < 0.05$).

TABLE 2. Correlation between body size, skeletal age and motor performance variables with the SSG technical actions by category

Variables	Conquering the ball [#]	Receiving the ball	Neutral ball	Losing the ball	Playing an offensive ball	Executing a successful shot [#]
	r (CI 95%)	r (CI 95%)	r (CI 95%)	r (CI 95%)	r (CI 95%)	r (CI 95%)
U-13 (n = 24)						
Skeletal age (years) [#]	0.37 (0.05–0.67)	0.08 (-0.32–0.48)	-0.10 (-0.48–0.32)	-0.32 (-0.63–0.11)	0.28 (-0.12–0.62)	0.34 (-0.13–0.69)
Body mass (kg)	0.48 (0.09–0.74)*	0.09 (-0.32–0.48)	-0.06 (-0.45–0.35)	-0.34 (-0.65–0.08)	0.27 (-0.15–0.61)	0.46 (0.06–0.73)*
Stature (cm)	0.33 (-0.07–0.65)	0.06 (-0.35–0.45)	-0.07 (-0.46–0.34)	-0.42 (-0.70 – -0.02)*	0.17 (-0.25–0.53)	0.48 (0.10–0.74)*
Fat free mass (kg)	0.45 (0.05–0.71)*	-0.06 (-0.45–0.35)	-0.20 (-0.55–0.22)	-0.32 (-0.63–0.10)	0.18 (-0.24–0.54)	0.43 (0.03–0.71)*
Locomotion (score)	0.12 (-0.31–0.48)	0.32 (-0.31–0.49)	-0.41 (-0.42–0.38)	0.41 (-0.28–0.51)	-0.34 (-0.44–0.36)	0.13 (-0.63–0.76)
Balance (score)	0.34 (-0.07–0.66)	-0.06 (-0.45–0.35)	0.10 (-0.32–0.48)	-0.16 (-0.53–0.26)	-0.23 (-0.58–0.18)	0.03 (-0.38–0.42)
Manipulation (score)	0.52 (0.15–0.76)*	0.31 (-0.11–0.63)	0.14 (-0.28–0.51)	-0.23 (-0.59–0.19)	0.30 (-0.12–0.63)	0.50 (0.12–0.75)*
U-15 (n = 58)						
Skeletal age (years) [#]	0.12 (-0.16–0.37)	-0.30 (-0.52– -0.05)*	-0.29 (-0.50– -0.02)*	-0.09 (-0.32–0.19)	0.19 (-0.41–0.08)	-0.18 (-0.46–0.02)
Body mass (kg)	-0.06 (-0.31– 0.20)	-0.25 (-0.48–0.01)	-0.29 (-0.51– -0.03)*	-0.03 (-0.29–0.23)	-0.28 (-0.50–0.02)*	-0.17 (-0.41–0.09)
Stature (cm)	-0.10 (-0.34–0.16)	-0.22 (-0.46–0.04)	-0.22 (-0.45–0.04)	0.09 (-0.34–0.17)	-0.23 (-0.46–0.03)	-0.17 (-0.40–0.10)
Fat free mass (kg)	-0.06 (-0.31–0.20)	-0.14 (-0.39–0.12)	-0.20 (-0.44–0.06)	-0.14 (-0.36–0.15)	-0.22 (-0.45–0.04)	-0.17 (-0.39–0.11)
Locomotion (score)	-0.14 (-0.50–0.25)	-0.04 (-0.40–0.32)	-0.07 (-0.41–0.30)	-0.16 (-0.49–0.21)	-0.42 (-0.68–0.07)	-0.27 (-0.59–0.11)
Balance (score)	0.15 (-0.11–0.39)	0.17 (-0.09–0.41)	0.07 (-0.19–0.32)	0.26 (0.01–0.49)*	-0.05 (-0.30–0.21)	0.01 (-0.25–0.26)
Manipulation (score)	-0.13 (-0.39–0.12)	0.23 (-0.03–0.45)	0.04 (-0.22–0.29)	-0.04 (-0.29–0.22)	-0.08 (-0.33–0.18)	0.01 (-0.20–0.31)

Note: [#] = transformed data log¹⁰; * = significant correlations ($P < 0.05$).

Table 2 presents correlations between body size, skeletal age and motor performance and number of technical actions stratified by category. For the U-13 category, the number of technical actions showed weak to moderate positive correlations with body size and motor performance indicators ($P < 0.05$). Body size (body mass and fat-free mass) presented positive correlations with CB and SS. In addition, manipulation presented positive correlations with CB and SS. Regarding the number of technical actions, smaller soccer players presented a higher number of LB.

In the U-15 category, players with lower weight or lower skeletal age showed weak inverse correlations with number of technical

actions ($P < 0.05$); SA was significantly correlated with RB and NB, and body mass showed significant correlations with NB and OB. In addition, balance was positively correlated with LB.

The association between body size, skeletal age, motor performance and number of technical actions in SSG is described in Table 3. Regression models were applied only to technical variables that presented significant correlations with body size and motor performance in the U-13 category. The analysis revealed that the number of technical actions CB and SS was positively associated with body size indicators ($P < 0.05$). However, when using the adjusted model (models 2 and 3), associations did not present significance. In motor

TABLE 3. Linear regression between body size, skeletal age, motor performance and SSG technical actions for U-13 (n = 24) category.

Independent variables	Adjustment variables	Linear regression								
		Conquering the ball [#]			Losing the ball			Executing a successful shot [#]		
		β	R ²	P	β	R ²	P	β	R ²	P
Body Mass	Model 1	0.48	0.23	0.02*	–	–	–	0.46	0.21	0.02*
	Model 2	0.30	0.34	0.15	–	–	–	0.29	0.31	0.17
	Model 3	0.33	0.23	0.34	–	–	–	0.26	0.22	0.46
Stature	Model 1	–	–	–	-0.42	0.17	0.04*	0.48	0.23	0.02*
	Model 2	–	–	–	-0.40	0.18	0.09	0.32	0.33	0.13
	Model 3	–	–	–	-0.51	0.18	0.14	0.34	0.24	0.30
Fat free mass	Model 1	0.45	0.20	0.03*	–	–	–	0.43	0.19	0.03*
	Model 2	0.34	0.30	0.13	–	–	–	0.29	0.32	0.14
	Model 3	0.26	0.24	0.32	–	–	–	0.24	0.23	0.36
Manipulative	Model 1	0.52	0.27	0.01*	–	–	–	0.50	0.25	0.01*
	Model 3	0.40	0.33	0.61	–	–	–	0.37	0.31	0.08
	Model 4	0.45	0.44	0.03*	–	–	–	0.36	0.33	0.11

Note: Model 1 = Gross Value; Model 2 = Adjusted for motor performance (manipulation); Model 3 = Adjusted for skeletal age; Model 4 = Adjusted for body size variables (body mass, stature and fat free mass); * = significant correlations (P < 0.05).

TABLE 4. Linear regression between body size, skeletal age, motor performance and SSG technical actions for U-15 (n = 58) category

Independent variables	Adjustment variables	Linear regression											
		Receiving the ball			Neutral ball			Losing the ball			Playing an offensive ball		
		β	R ²	P	β	R ²	P	β	R ²	P	β	R ²	P
Skeletal age [#]	Model 1	-0.31	0.09	0.02*	-0.29	0.08	0.03*	–	–	–	–	–	–
	Model 2	-0.31	0.12	0.02*	-0.28	0.08	0.03*	–	–	–	–	–	–
	Model 4	-0.26	0.13	0.16	-0.17	0.11	0.40	–	–	–	–	–	–
Body Mass	Model 1	–	–	–	-0.29	-0.08	0.03*	–	–	–	-0.28	-0.08	0.03*
	Model 2	–	–	–	-0.31	0.10	0.02*	–	–	–	-0.28	0.08	0.04*
	Model 3	–	–	–	-0.18	0.10	0.31	–	–	–	-0.30	0.08	0.10
Balance	Model 1	–	–	–	–	–	–	0.26	0.07	0.05*	–	–	–
	Model 3	–	–	–	–	–	–	0.26	0.08	0.05*	–	–	–
	Model 4	–	–	–	–	–	–	0.32	0.13	0.02*	–	–	–

Note: [#] = transformed data log¹⁰; Model 1 = Gross Value; Model 2 = Adjusted for motor performance (Balance); Model 3 = Adjusted for bone age; Model 4 = Adjusted for body size variables (body mass, stature and fat free mass); * = significant correlations (P < 0.05).

performance, it was observed that for each extra unit in the manipulation test, the number of technical actions increased by 0.52 in CB and 0.50 in SS. Although no significant associations were found when motor performance was adjusted for skeletal age (model 3) and body size indicators (model 4) for SS, for CB, the association maintained its significance (P = 0.03), demonstrating that this association was not affected by body size variables.

Table 4 shows the association between body size, skeletal age, motor performance and number of technical actions in SSG in the

U-15 category. The results show negative associations between SA and number of technical actions (RB and NB) and body size with number of technical actions (NB and OB) (P < 0.05). For motor performance, positive associations were observed between balance and LB. Associations between SA or body size and number of technical actions were not affected by motor performance (balance), while associations of SA were affected by body size variables and body mass by SA. Regarding associations between balance and LB, the influence of body size and SA was not significant.

DISCUSSION

The aim of this study was to verify the impact of body size and motor performance variables on the number of technical actions performed during SSG in young soccer players. The main result of this study was that the number of technical actions in SSG was positively associated with body size and motor performance in the U-13 category, and negatively associated with skeletal age, body size and motor performance in the U-15 category, except for the balance test, which was positively associated with LB technical action.

In our study, which used an ecological model of the game to observe the number of technical actions in SSG, no differences were observed between age groups U-13 and U-15. This fact suggests that the technical elements of the game occurred similarly in different age groups; however, the relative effects of body size on the number of technical actions were still inconclusive using the ecological model in the different age groups.

In the U-13 category, taller, heavier players and those with better performance in the manipulation test showed higher involvement in SSG, with a higher number of defensive (CB) and offensive (SS) actions, whereas shorter players performed a higher number of LB actions. Previous studies have consistently shown that soccer players advanced in biological maturation outperform their peers in strength, height, and body mass [3, 5, 6, 8], but there is still a lack of information about the influence of anthropometric factors [4–6] and maturational factors [39] on the number of technical actions in SSG performed by young soccer players. The present results showed that in the U-13 category, body size influenced the number of technical actions performed during SSG, indicating that taller and heavier players are more prone to present higher participation in SSG (higher involvement) regardless of their skeletal age, which could be a confounding factor, and consequently, higher likelihood of presenting better performance and advantages to be selected for further phases of the training process. Interestingly, this influence was also evident due to the linear regression results, which showed that controlling for factors such as body size and SA, associations between these variables and number of technical actions were not significant.

Contrary to results observed for U-13, in the U-15 category, body size and SA presented an inverse correlation with number of technical actions. In this age category, players with lower body mass and SA presented higher involvement in SSG technical actions (RB, NB, and OB), receiving a higher number of passes, and performing a higher number of both neutral and offensive passes. These findings suggest that in this age category, factors other than anthropometric variables may be involved in performance during SSG, and these factors may be highly associated with technical skills and tactical knowledge of players, regardless of body dimensions.

In a 10-year longitudinal follow-up study, Figueiredo et al. [40] evaluated young soccer players from 11–13 to 22–25 years of age. The authors observed that players who reached professionalization and remained active in soccer were those who presented at the age of 13 years, lower SA, lower body mass, greater ball control and

a higher score in the pass test. In addition, those with higher performance in specific skill tests at the age of 15 years reached national level teams. In a study conducted by Craig and Swinton [41], the authors followed 512 young Scottish soccer players aged 10–17 over ten years. The authors observed that successful players have advantage in anthropometric and physical profiles; however, these differences cannot be considered a reliable source for predicting success in professional soccer, highlighting the need for monitoring other characteristics, including technical skills.

Regarding motor performance, U-13 soccer players who showed better motor performance in the manipulation test performed a higher number of technical actions in CB and SS. In U-15, those with better results in the balance tests had higher LB. We expected that the results in the U-15 category would follow correlations obtained in the U-13 category, in which U-13 players presented positive associations between the motor test and technical actions. A possible explanation for this finding in the U-15 category is related to motor tasks, such as dynamic balance, which require certain coordination, strength, and power. In this case, players with advanced SA probably showed better motor task performance. This positive relationship between motor tests and maturity is related to neuromuscular maturation and the recruitment of specific muscle fibres [42]. In addition, the effect of playing position, which was not controlled in this study, may have influenced these associations [43], since mainly U-15 category forwards with better balance are probably more involved in 1 vs 1 situations due to their greater strength and power to determine the outcome, but this hypothesis should be empirically tested in further studies.

Partially contradicting our initial hypothesis, the results of the present study suggest that the influence of body size and maturity indicators become less important in older athletes, and smaller players and those with late maturity present higher involvement in SSG due to the higher number of technical actions performed, especially for those related to offensive actions. However, there is a need to look beyond the current moment of the performance of young soccer players. Body growth and maturity in each category may present different outcomes related to the number of technical actions in a soccer match. The non-exclusion of these players with smaller body size in the U-13 and especially in the U-15 category should be considered because their permanence in the training process could contribute to their long-term development [44], since studies point out that after 17 years of age, late athletes tend not to differ in size and performance from early athletes, demonstrating stabilization [45]. Thus, late athletes could have better athletic potential as adults, due to the various challenges faced in the training process to remain in the group of soccer players and not to be prematurely excluded [46].

As study limitations, we highlight the cross-sectional design, which is unable to follow variations in the performance of young soccer players over time and the low number of late players. In addition, the small sample size due to division by age groups makes it impossible to perform analyses by playing position. Nevertheless,

the present study contributes to advancing of the understanding of relationships between the number of technical actions in SSG and body size, maturation and motor performance. The results obtained are novel and unique, add important information to the literature, and provide important clarifications for professionals who work with the selection and development of young soccer players. Therefore, future studies with longitudinal designs are needed, according to changes caused by body size during the growth process in motor performance and technical performance of young players.

CONCLUSIONS

In conclusion, body size, skeletal age and motor performance can differently influence the number of performed technical actions when U-13 and U-15 categories are compared. In the U-13 category, the positive influence of body size and motor performance indicators shows that heavier players and those with better motor performance are at an advantage in performing a higher number of technical actions CB and

SS). In the U-15 category, advantages promoted by physical growth were not observed. Players with lower body mass and SA had a higher number of performed technical actions (RB, NB and OB) during SSG.

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Conflict of interest

The authors declared no conflict of interests regarding the publication of this manuscript.

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SUPPLEMENTARY TABLE 1. Normality and homogeneity of motor performance and number of technical actions

Variables	Levene Test	P	Skewness	Std. Error of Skewness	Z Skewness	Kurtosis	Std. Error Of Kurtosis	Z Kurtosis
Locomotion (score)	1.494	0.225	0.147	0.266	0.55	0.740	0.526	1.40
Balance (score)	3.184	0.078	-0.075	0.266	1.40	-0.077	0.526	-0.14
Manipulation (score)	0.125	0.725	0.179	0.266	0.67	-0.416	0.526	-0.79
Conquering the ball (number of actions) [#]	0.257	0.614	0.477	0.276	1.72	-0.516	0.545	-0.94
Receiving the ball (number of actions)	0.702	0.405	0.153	0.266	0.57	-0.516	0.545	-0.94
Neutral ball (number of actions)	0.057	0.812	0.269	0.266	1.01	-0.141	0.526	-0.26
Losing the ball (number of actions)	0.000	0.987	-0.179	0.276	-0.64	-0.969	0.545	-1.77
Playing an offensive ball (number of actions)	3.423	0.068	0.118	0.295	0.40	-0.207	0.582	-0.35
Executing a successful shot (number of actions) [#]	0.007	0.933	0.376	0.281	1.33	-0.736	0.555	-1.32

Note: [#] = transformed data $\log^{10}$;

SUPPLEMENTARY TABLE 2. Sample description by category and playing position

Variables	U-13 (n = 24)					U-15 (n = 58)				
	Defender (n = 9)	Midfielder (n = 5)	Forward (n = 10)	F	P	Defender (n = 18)	Midfielder (n = 25)	Forward (n = 15)	F	P
Chronological age (years)	12,9 ± 0,5	12,9 ± 0,5	12,9 ± 0,7	0,006	0,994	14,9 ± 0,6	15,0 ± 0,5	15,1 ± 0,5	0,495	0,612
Skeletal age (years)	13,3 ± 1,3	12,4 ± 0,9	12,9 ± 1,5	0,742	0,488	15,4 ± 0,8	15,5 ± 0,7	15,2 ± 1,1	0,420	0,659
Body mass (kg)	50,1 ± 10,5	43,8 ± 6,4	45,3 ± 8,9	0,996	0,386	63,9 ± 5,9	62,3 ± 6,3	61,1 ± 7,8	0,769	0,469
Stature (cm)	162,3 ± 10,8	158,7 ± 7,4	157,1 ± 10,8	0,602	0,557	176,8 ± 7,2	171,9 ± 5,4 ^a	173,2 ± 5,4	3,530	0,036
Fat free mass (kg)	42,5 ± 12,0	39,9 ± 6,2	40,3 ± 9,0	0,159	0,854	57,5 ± 6,1	55,7 ± 5,4	55,4 ± 7,0	0,632	0,536
Locomotion (score)	-0,05 ± 0,3	0,3 ± 0,6	-0,08 ± 0,4	1,296	0,295	0,09 ± 0,5	-0,01 ± 0,6	-0,1 ± 0,5	0,523	0,596
Balance (score)	-0,15 ± 0,8	0,5 ± 0,6	-0,11 ± 1,02	1,108	0,349	-0,1 ± 0,6	0,0 ± 0,7	0,1 ± 0,7	0,501	0,609
Manipulation (score)	-0,12 ± 0,7	-0,03 ± 0,6	0,13 ± 1,0	0,218	0,806	-0,1 ± 0,9	-0,02 ± 0,07	0,2 ± 1,0	0,583	0,562
CB (n. of actions) [#]	2,0 ± 1,3	2,2 ± 1,3	2,1 ± 1,7	0,029	0,971	1,5 ± 1,1	1,9 ± 1,3	2,1 ± 2,3	0,574	0,567
RB (n. of actions)	9,8 ± 3,7	11,0 ± 1,9	11,9 ± 3,6	0,941	0,406	9,5 ± 3,1	11,0 ± 3,8	11,0 ± 3,4	1,089	0,344
NB (n. of actions)	7,0 ± 2,2	7,8 ± 1,9	5,9 ± 3,9	0,719	0,499	6,4 ± 2,7	7,5 ± 2,8	6,0 ± 3,7	1,309	0,278
LB (n. of actions)	1,8 ± 1,3	1,6 ± 1,1	3,5 ± 1,7 ^{a,b}	4,339	0,026	3,0 ± 2,0	2,6 ± 1,5	2,6 ± 1,9	0,311	0,734
OB (n. of actions)	1,5 ± 0,9	1,4 ± 1,3	1,8 ± 1,5	0,192	0,827	1,4 ± 1,1	2,0 ± 1,4	2,3 ± 2,3 ^a	3,417	0,040
SS (n. of actions) [#]	1,2 ± 1,0	1,8 ± 1,6	2,1 ± 1,8	0,823	0,453	1,8 ± 1,5	2,2 ± 1,4	2,7 ± 2,2	1,366	0,264

Note: [#] = transformed data log¹⁰; CB = Conquering the ball; RB = Receiving the ball; NB = Neutral ball; LB = Losing the ball; OB = Playing an offensive ball; SS = Executing a successful shot.

Monitoring training load in youth soccer players: effects of a six-week preparatory training program and the association between external and internal loads

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ABSTRACT: This study examined the effects of a six-week preparatory training program on physical performance and physiological adaptations in junior soccer players. Additionally, we investigated whether a relationship existed between external and internal loads. Youth soccer players (aged 16 years old) from a youth football academy participated in six weeks of pre-conditioning training. Wireless Polar Team Pro and Polar heart rate sensors (H10) were used to monitor physical performance indicators (sprint and acceleration scores, covered distance, maximum and average speed and duration), physiological responses (maximum and average heart rate [HR] and R-R interval, time in HR zones 4+5, and heart rate variability [HRV]), and training load score. Additionally, muscle status and rating of perceived exertion (RPE) scores were measured using digital questionnaires. Significant increases were observed in the majority of physical performance indicators [i.e., sprints ($p = 0.015$, $ES = 1.02$), acceleration ($p = 0.014$, $ES = 1$), total distance ($p = 0.02$, $ES = 0.87$), as well as maximum speed ($p = 0.02$, $ES = 0.87$)]. A trend towards improvement was observed in the remaining performance indicators (i.e., distance/min and avg speed; $ES = 0.6$), training load ($ES = 0.2$), muscle status ($ES = 0.3$), and all physiological responses parameters ($ES = 0.1$ to 0.6). Significant correlations were found between the majority of external load parameters (i.e., performance indicators) and objective (i.e., physiological responses) and subjective (i.e., RPE, muscle status) internal load parameters ($p < 0.001$). The highest number of moderate-large correlations were registered between performance indicators and time in HR zone 4+5 ($0.58 < r < 0.82$), training load ($0.53 < r < 0.83$), average HR ($0.50 < r < 0.87$), maximal HR ($0.51 < r < 0.54$) and average R-R interval ($0.58 < r < 0.76$). HR zone 4+5, average and maximal HR, average R-R interval, and training load score may help control training parameters and reduce the risk of under- or over-training in youth soccer players. However, these conclusions should be confirmed and replicated in future studies with more diverse subject populations.

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INTRODUCTION

Soccer is one of the most popular sports in the world, and top-level performance depends on physical fitness, psychological factors, technical skills, and team tactics [1]. In order to best prepare players to perform well during a match, while reducing risk of injury, training load is often recorded and monitored [2]. It is important to measure the physical loads applied to each player (e.g., distance covered, accelerations), and the subsequent physiological response, such as heart rate (HR) or subjective level of effort. This difference between these parameters is referred to as external and internal load [3–5]; there are numerous parameters for both external and internal load that are used in training management.

Recording the loads in soccer is often completed via the monitoring of training. “Training monitoring” is the systematic collection of data describing the amount, intensity, or content of the training [6], and is considered an effective method for training control [7]. Furthermore, training control is the visualization and objectification of a training process using appropriate performance parameters and technical instruments [6]. Training control allows the trainer to compare planning and performance, with specific regard to the athlete’s age, gender and performance level [6]. Based on training monitoring’s data, it is decided daily whether an athlete is ready for training or competition in order to create an optimal balance between load and recovery, which is essential for improving athletic performance [8].

In addition, periodization is used to optimize load management [9, 10]. Weekly periodization occurs when players experience varied training loads on different training days; over a longer period the load is steadily increased over three weeks, reduced in the fourth week, and then subsequently increased again [11]. The reduction during the 4th week, is referred to as tapering and increases game readiness [12, 13]. During the preparation phase, a gradual increase of the training load has been shown to reduce the risk of injury, while maintaining or even increasing performance throughout the season [11].

It is already established that there is a relationship between external and internal stress parameters [14, 15] as well as between objective and subjective internal exertion parameters [4]. In particular, significant correlations exist between athletes’ rating of perceived exertion (RPE) and different external (e.g., covered distance, speed,

acceleration) and internal (e.g., HR) load parameters [14, 15]. These data suggest both external and internal load measurements should be considered for training management [15]. However, most of these studies have primarily examined the effects of soccer training programs on external and/or internal load, as well as the possible relationship between internal and external loads, among adult professional soccer players. A paucity of data is available in youth athletes, who require special consideration given that they not only train for soccer, but go to school during the week. Therefore, we investigated whether a six-week preparation phase increases physical performance and generates physiological adaptations in junior soccer players. Furthermore, we examined the relationship between external and internal stress parameters.

MATERIALS AND METHODS

An observational study was carried out to evaluate the development of subjective and objective load parameters in youth soccer players (i.e., 16 years old) following a six-week preparation phase. The Polar Team Pro GPS system from Polar Electro GmbH (Büttelborn, Germany) and a Wellness-Questionnaire from the Science on Field GmbH in Leipzig were used to measure load parameters. Data were collected in the first week of the preparation phase and again six weeks later, during the first week of the competitive phase during the 2020/2021 season. Both test sessions were part of the training program and were programmed on the same day of the week (Tuesday) and the same time of the day (afternoon) to minimize the effect of diurnal biological variations [16–18]. Tuesday was chosen as the control day in each case, as the soccer conditioning training took place on this day in both weeks (see Figure 1).

Participants

A total of 19 soccer players from a U17 junior training centre were recruited to participate in the present study. Due to the Covid-19 pandemic and the associated restrictions as well as illnesses and/or injuries, 10 participants poorly adhered to the training program and were excluded. At the end of the study period, data from nine male players (age: 16 years old) were analysed and included in the final results.

After providing a detailed explanation about the study aims, design, and benefits, written informed consent was obtained from the parents.

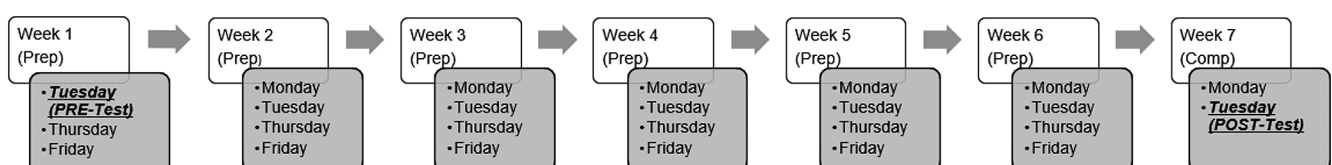


FIG. 1. Schedule of the data collection during six-week football training. Prep: Preparation phase; Comp: competition phase.

The protocol was approved by the local review board and the study was conducted according to the declaration of Helsinki.

The six-week preparatory training program

Participants reported to the sport club four times per week (i.e., Monday, Tuesday, Thursday and Friday) to complete their assigned training program with a game scheduled each weekend. In the first two weeks, the focus was on ball possession with high volume and low intensity to improve football fitness [11]. On the third week, the focus was on losing the ball. Then, on the fourth week more

defending exercises were programmed with a simultaneous increase in intensity and decrease in volume. The last two weeks training program focused on winning the ball with continuing increase in intensity and decrease in volume [11]. This set-up aims to progressively involve the players in high intensity exercises in order to improve their ability to perform more football-specific actions per minute with reduced risk of injury [11]. All training sessions consisted of football-based games, which, by changing the number of players, size of the pitch and work-rest ratio, targeted different training goals [11].

TABLE 1. Selected physical performance and heart rate data from the Polar team

Physical Performance parameters	
Sprint score	A sprint is counted as a sprint when the player reaches an acceleration of 2.8 m/s ² regardless of the duration or distance of the sprint
Acceleration score	Summary of the number of negative and positive accelerations from 2 m/s ² in a training session
Total distance (m)	Total distance during the training session. (in meters).
Distance / min (m/min)	Average distance per minute during the training session. (in meters).
Maximum speed (km/h)	Maximum speed during the training session. (kilometre/hour)
Average speed (km/h)	Average speed during the training session. (kilometre/hour)
Duration (min)	Total training duration in min, starts with entering and ends with leaving the court
Physiological parameters	
Maximal heart rate (HRmax)	Maximal heart rate during the training session calculated as “beat/minute” and as % of the maximal heart rate (% HR max).
Average heart rate (HRavg)	Average heart rate during the training session calculated as “beat/minute” and as % of the maximal heart rate (% HR max).
Average RR interval (Avg RR)	Average beat-to-beat interval during the training session (millisecond). An increase over time means that fitness is improving.
Maximum RR interval (Max RR)	Maximum time between successive heartbeats (beat-to-beat interval) recorded during the training session (milliseconds).
HRV (RMSSD)	The root mean square of successive differences between normal heartbeats (RMSSD) is obtained by first calculating each successive time difference between heartbeats in milliseconds. Each of the values is then squared and the result is averaged before the square root of the total is obtained. The RMSSD reflects the beat-to-beat variance in heart rate and reflects short-term heart rate variability HRV [19]. High HRV is related to improved health and indicates that the heart is functioning well, and that the autonomic nervous system is adapting to the demands placed on it [20].
Time in HR zone 1	Heart rate (HR) zones are a way to monitor how the training intensity is. There are five heart rate zones based on the intensity of training with regard to the maximum heart rate. The % of the maximum heart rate in each zone are as following: Zone 1: 50–60%, Zone 2: 60–70%, Zone 3: 70–80%, Zone 4: 80–90%, Zone 5: 90–100% [21]. In the present paper, the time in heart rate zone 4 and 5 was added, because these two zones run in anaerobic energy supply
Time in HR zone 2	
Time in HR zone 3	
Time in HR zone 4	
Time in HR zone 5	
Training Load	
Training load score	Training Load includes textual feedback on the strenuousness of a single training session. It is based on intensity and duration of a training session with the intensity of a session is measured using HR and the calculation is further affected by personal information, such as age, sex, weight, VO _{2max} , and training history. As participant's fitness improves, same training session creates less training load (Polar).

Measurements

The wireless Polar Team Pro was used for this investigation. Sprint score, acceleration score, total distance, distance/min, maximum speed, average speed, and duration were examined as physical performance parameters; maximal HR, average HR, average R-R interval, maximal R-R interval, heart rate variability (HRV), and time in heart rate zones 4+5 were examined as physiological parameters. Training load score was also examined using this system.

The sensors of the system include an integrated GPS (measures at 10 Hz), a 10 Hz MEMS motion sensor, a 200 Hz accelerometer, and a sensor to measure the HR [21]. These sensors are attached to a chest strap, which is placed on the xiphoid process of the sternum with the chest strap fitted around the participant's chest [22]. The Polar chest strap has been previously validated against the electrocardiogram gold standard and collects and processes HR measurements by detecting the electrical signals of the heart [23].

Each player received a sensor from Polar before the training session, which they wore for the entirety of the training session [24]. Each player received the same sensor on all training days to reduce measurement error [25, 26]. Table 1 shows detailed descriptions of the physical performance and HR parameters selected from the Polar Team Pro system.

The Wellness-Questionnaire was collected with the help of a web-app especially developed for this club. This application was developed by Science on Field GmbH in Leipzig and is based on a simple questionnaire system in which the players answer ten wellness questions on a 0–10 scale each morning.

The questionnaire contained 10 questions. The following questions were relevant for this study: “How is your muscle status today?” and “How was the training intensity the day before? The question “How was the training intensity on the previous day” corresponds to the question about the RPE from the previous day's training. The authors of this paper did not have access to the data of all other eight questions of the application, as these are subject to the data protection of the junior training centre.

After each training session, the current muscle condition and training intensity of the previous day was recorded using the aforementioned web app. Players were required to complete the survey by 12:00h.

Statistical Analysis

Data are presented as mean $\pm$ standard deviation (SD) and were analyzed using the Jamovi software (1.8.1, <https://www.jamovi.org/>). Descriptive statistics (mean $\pm$ SD) was calculated for muscle status, training intensity of the day before, number of sprints, accelerations, total distance, distance/min, maximum speed, average speed, duration, maximal HR, average HR, time spent in 80–100% the maximum HR, and the training load.

For the six-week training period, the Shapiro-Wilk test was used to assess data normality. Paired t-tests were performed to compare normally distributed data collected during the first vs. the second

test session and Wilcoxon test was performed for non-normal distribution. Also, mean difference with 95% Confidence Interval (95%CI) and the effect size using Cohen's d with 95%CI was calculated and interpreted as follows: < 0.2 as trivial, 0.20 – 0.59 as small, 0.60 – 1.19 as moderate, 1.20 – 1.99 as large and ≥ 2.0 as very large [27].

For correlations, the normality of the pooled values of all training units over the six weeks was checked with the Shapiro-Wilk test. Pearson correlation was performed for bi-normally distributed data and Spearman correlation was performed for non-normal distribution. The Rho-value was calculated as the Pearson's and Spearman's correlation effect size and interpreted as < 0.1 – trivial; 0.10 to 0.29 – small; 0.30 to 0.49 – moderate; 0.50 to 0.69 – large; 0.70 to 0.89 – very large; ≥ 0.90 – nearly perfect [27]. Significance for all analyses was accepted at the level of $p < 0.05$.

In order to calculate the gain or decrease over the six-week preparation period, difference scores (Δ) from PRE- (T1) to POST- (T2) test session ($\Delta = T2 - T1$) were calculated for all parameters. Additionally, based on tests and re-tests [28], the standard error of measurement (SEM) was established for HR- and HRV-related parameters, as well as for physical performance and strenuousness indicators, as previously described [29, 30]. Two times the SEM is considered the threshold for a true physiological adaptation beyond what would be expected from technical and/or biological variability [30, 31]. Therefore, responsiveness to the six weeks' physical preparation training was defined as changes exceeding two times the SEM in favor of beneficial changes. The responsiveness threshold in each selected parameter, as well as the prevalence of responders and non-responders to training and detraining, have been reported in the results section.

RESULTS

Table 2 shows the mean and standard deviation of all tested parameters measured during the PRE- and POST-test sessions, as well as the six week's averaged values.

The effect of six-week preparation period on physical performances

The values of physical performance parameters at PRE- and POST-test sessions are presented in Figure 2. Statistical analysis revealed significantly higher values at POST-test compared to PRE-test for number of sprints [$p = 0.015$, $ES = 1.02$ (moderate), mean difference = 7 ($1.74; 12.3$)], acceleration score [$p = 0.014$, $ES = 1$, mean difference = 74.1 ($53; 96.5$)], total covered distance [$p = 0.02$, $ES = 0.87$, mean difference = 1573 ($191; 1878$)], and maximum speed [$p = 0.02$, $ES = 0.87$, mean difference = 1.4 ($0.37; 2.85$)]. There were slight, non-significant increases in distance/min [$ES = 0.56$, mean difference = 6.5 ($-5; 9$)] and average speed [$ES = 0.6$, mean difference = 0.17 ($-0.59; 0.3$)] from PRE- to POST-test session ($p > 0.05$).

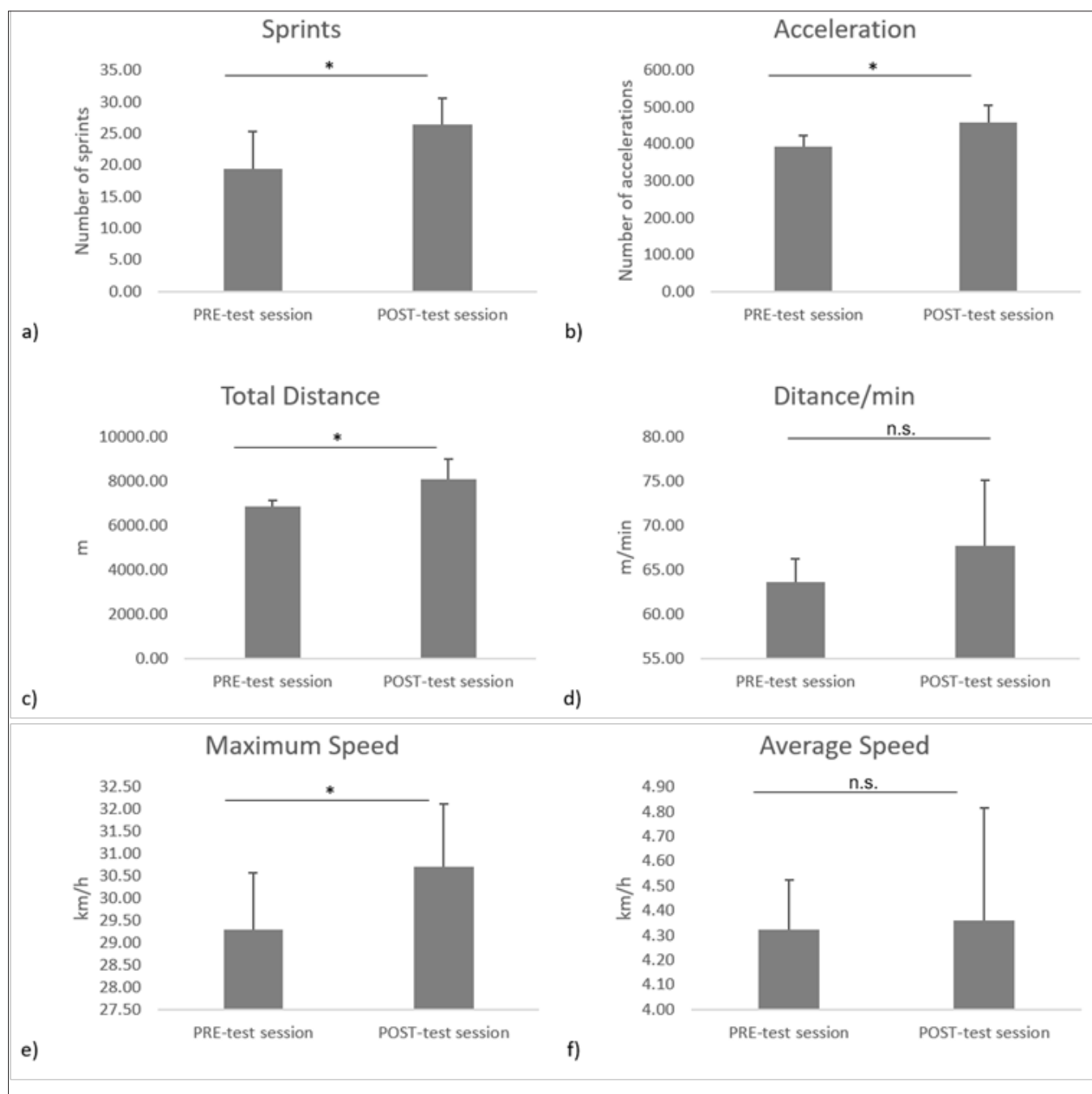


FIG. 2. Mean $\pm$ SD values of a) number of sprints, b) accelerations, c) total distance, d) distance/min, e) maximum speed, and f) average speed at PRE- and POST-test session, *: significant difference between PRE- and POST-test sessions with $p \leq 0.05$; n.s: means no significant difference between PRE- and POST-test sessions.

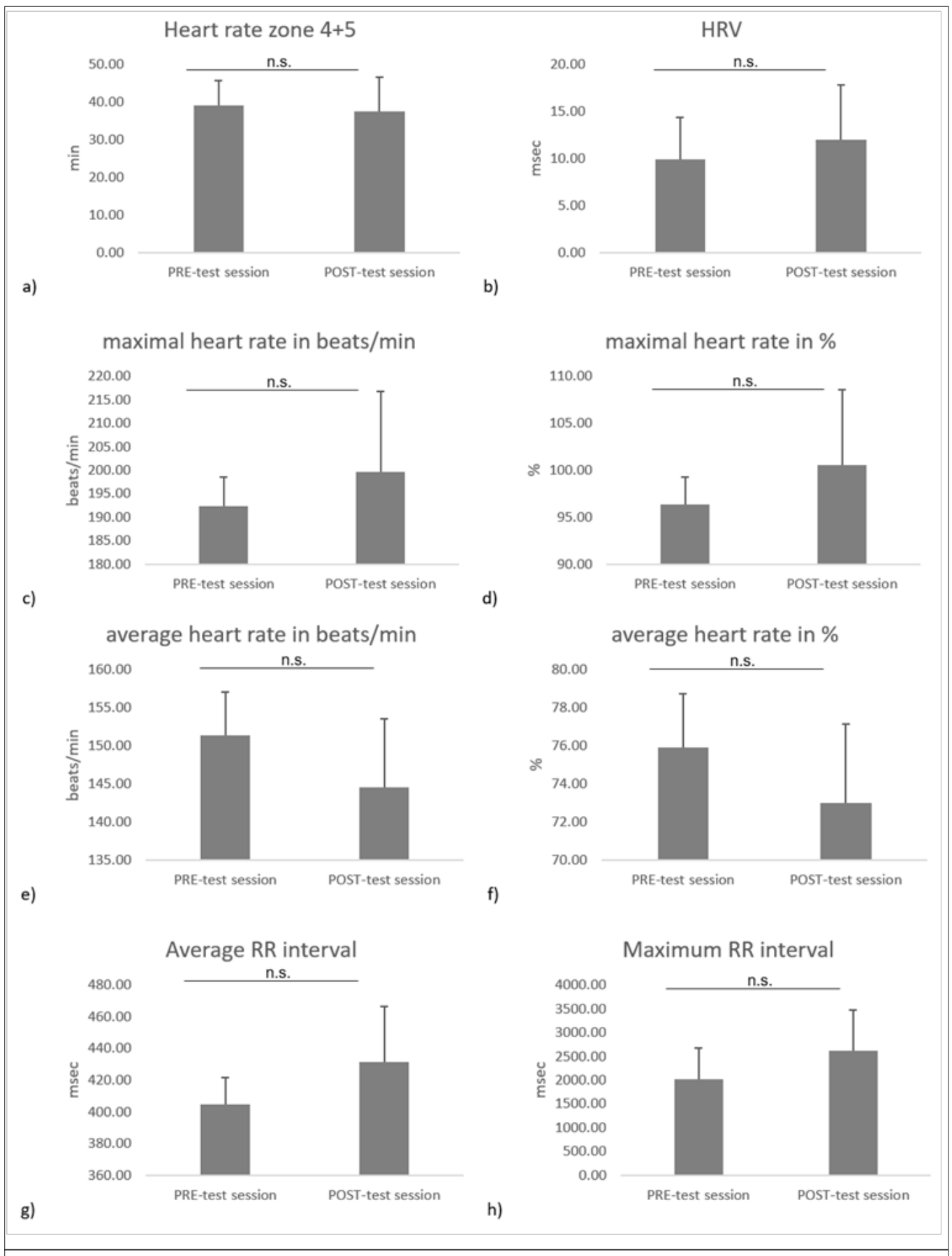


FIG. 3. Mean $\pm$ SD values of a) heart rate zone 4+5, b) HRV c) maximal heart rate in beats/min, d) maximal heart rate in %, e) average heart rate in beats/min f) average heart rate in %, g) average RR interval, and h) maximal RR interval at PRE- and POST-test session. n.s.: means no significant difference between PRE- and POST-test sessions.

TABLE 2. Mean and standard deviation (SD) of the examined parameters

Development over six weeks				
	Parameter	PRE-test session	POST-test session	six weeks' averaged values
Physical performance	Sprint score	19.44 ± 5.93	26.44 ± 4.09	12.55 ± 8.82
	Acceleration score	392.44 ± 30.6	458.11 ± 47.51	297.11 ± 92.69
	Total distance (m)	6847.22 ± 286.26	8099.44 ± 911.71	4763.21 ± 2139.98
	Distance/min (m/min)	63.67 ± 2.58	67.67 ± 7.48	51.49 ± 16.94
	Maximum speed (km/h)	29.29 ± 1.27	30.71 ± 1.42	26.24 ± 4.13
	Average speed (km/h)	4.32 ± 0.2	4.36 ± 0.45	4.05 ± 1.36
	Duration (min)	107.42 ± 0	120.0 ± 0	91.72 ± 19.59
Physiological responses	Maximal heart rate (beats/min)	192.33 ± 6.18	199.67 ± 17.03	189.11 ± 16.97
	Maximal heart rate (%)	96.33 ± 2.94	100.56 ± 7.96	95.25 ± 8.29
	Average heart rate (beats/min)	151.33 ± 5.77	144.56 ± 8.93	145.72 ± 17.60
	Average heart rate (%)	75.89 ± 2.85	73.0 ± 4.14	73.52 ± 8.79
	Average RR interval (msec)	404.89 ± 16.86	431.22 ± 35.23	425.22 ± 52.37
	Maximum RR interval (msec)	2019.56 ± 659.05	2620.67 ± 846.01	2369.80 ± 781.07
	HRV (msec)	9.89 ± 4.51	12.0 ± 5.83	11.11 ± 6.68
	Time in heart rate zone 4 + 5 (min)	39.18 ± 6.45	37.57 ± 9.10	25.17 ± 20.25
	Training load score (AU)	192.44 ± 25.4	202.11 ± 39.73	131.40 ± 64.38
	Muscle status	6.67 ± 1.89	7.0 ± 1.49	7.48 ± 1.60
	RPE of the previous day	3.89 ± 2.02	3.89 ± 2.18	5.38 ± 2.70

The effect of the six-week preparation period on physiological responses

Following the six-week preparation period, slight non-significant increases in HRV [$p = 0.31$, $ES = 0.4$, mean difference = 3 (-3;7)], maximal HR [$p = 0.22$, $ES = 0.44$, mean difference = 7.33 (-5.41;20.1) and $p = 0.14$, $ES = 0.54$, mean difference = 4.22 (-1.79;10.2) when expressed as beats/min and as %, respectively] and average [$p = 0.09$, $ES = 0.64$, mean difference = 26.3 (-5.37;58)] and maximal [$p = 0.16$, $ES = 0.56$, mean difference = 562 (-225;1399)] R-R intervals were measured during the POST- compared to the PRE-test session. In contrast, a slight non-significant decrease was registered following the six-week preparation period for time spent in HR zone 4+5 [$p = 0.7$, $ES = 0.13$, mean difference = -1.62 (-11;7.74)] and the average HR [$p = 0.12$, $ES = 0.57$, mean difference = -6.78 (-15.8;2.26) when expressed as beats/min and $p = 0.17$, $ES = 0.5$, mean difference = -2.89 (-7.33;1.55) when expressed as %]. The values of the physiological responses are shown in Figure 3.

The effect of the six-week preparation period on training load and wellness parameters

Statistical analysis showed slight no significant increase in training load [$p = 0.52$, $ES = 0.23$, mean difference = 9.67 (-23;42.4)] and muscle status [$p = 0.345$, $ES = 0.6$; mean difference = 1 (0;1.5)] from PRE- to POST-test. Additionally, mean values of the RPE of the previous day were unchanged from PRE- to POST-test [$p = 1.00$, $ES = 0$, mean difference = -0.000042 (-0.5;1)]. The results are presented in Figure 4.

Responsiveness of the U17 soccer players to the six-week preparation period

The prevalence of responders and non-responders to the six-week preparation training period are presented in Table 3. At least 2/3 of the players have been classified as responders to the beneficial training adaptation for total distance, average speed, average HR and HRV, while only 2 of the 9 players responded to the maximal HR training adaptation. For R-R and load score adaptations, approxi-

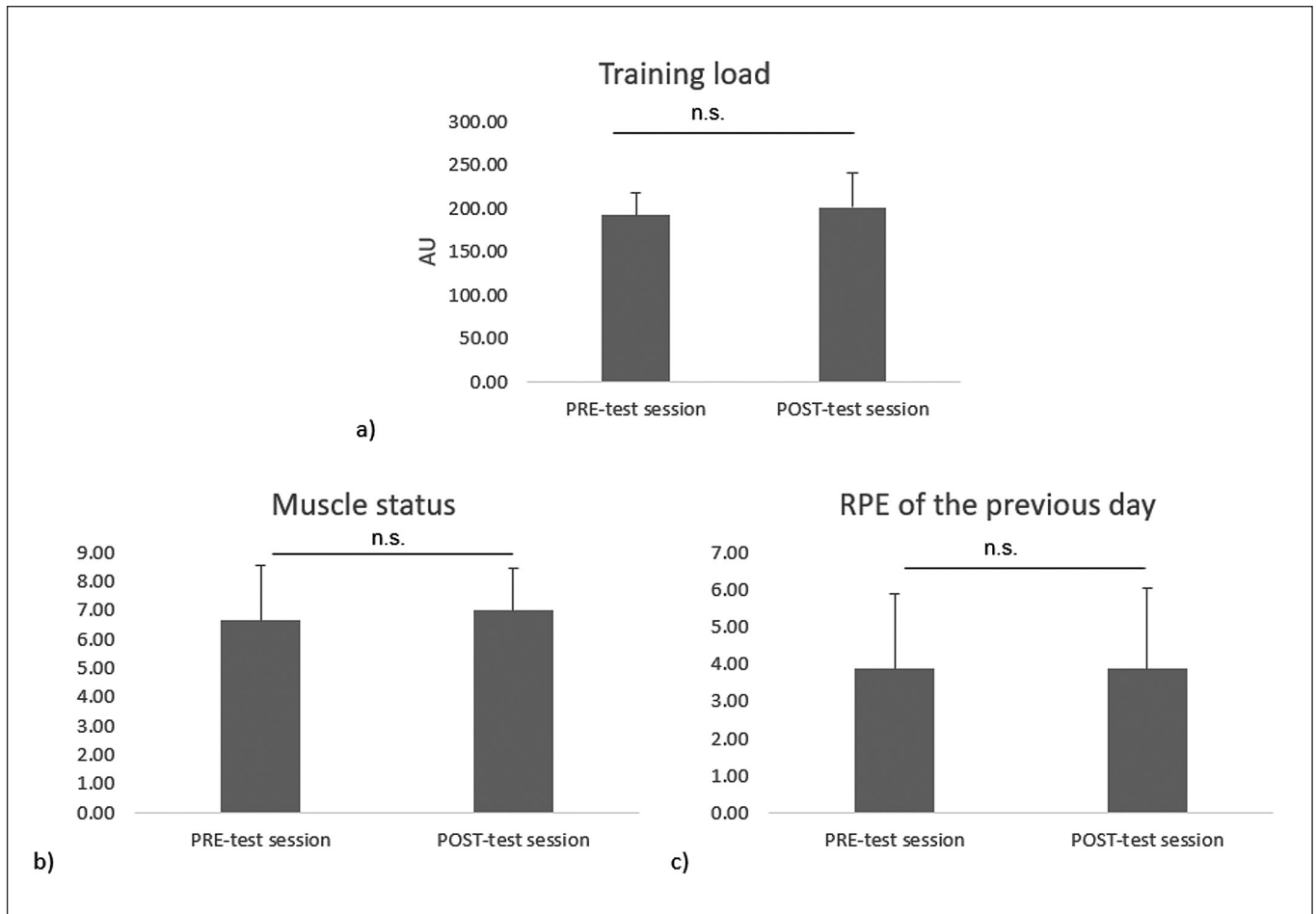


FIG. 4. Mean $\pm$ SD values of a) training load, b) muscle status, and c) RPE of the previous day at PRE- and POST-test session. n.s: means no significant difference between PRE- and POST-test sessions.

TABLE 3. Prevalence of responders and non-responders to training adaptations.

Participants Number	Responsiveness to Training Adaptations							
	HR (bpm)		HRV Related Parameters (msec)			Physical Performance and Strenuousness Indicators		
	HR Avg	HR Max	Max RR	Avg RR	HRV (RMSSD)	Total Distance(m)	Avg Speed (km/h)	Load Score
RT	-2.26	-2.01	241.85	22.01	1.3	71.16	0.07	11.9
Responders	6	2	5	5	6	8	7	4
Non-Responders	3	7	4	4	3	1	2	5
Non-responders %	33.33	77.78	44.44	44.44	33.33	11.11	22.22	55.56

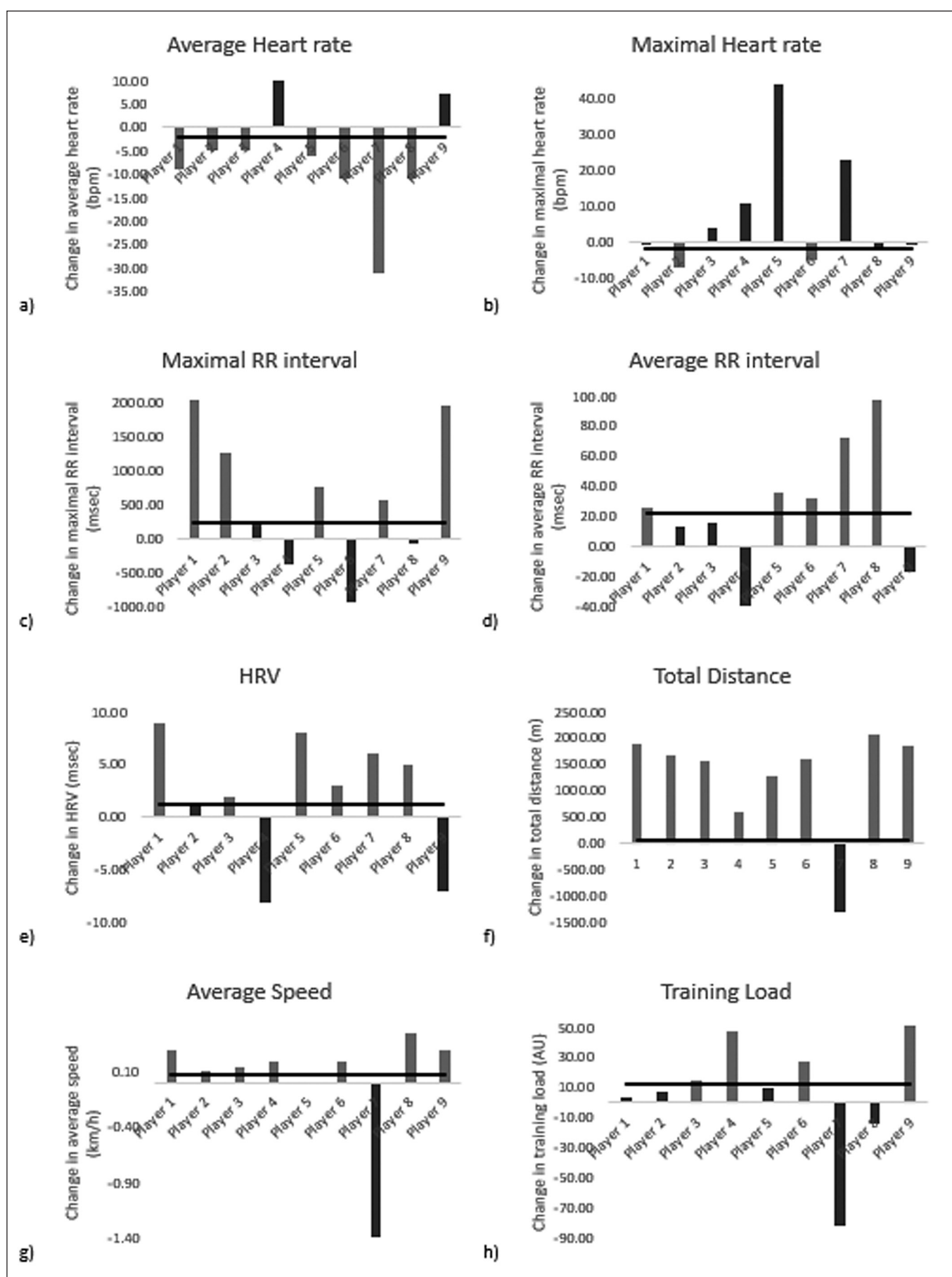


FIG. 5. Individual responsiveness scores to six-week training period.

mately half of the players were not responders. Individual responsiveness scores can be found in supplementary materials (Figure 5).

Relationship between external and internal loads in U17 soccer players

The correlation between the external and internal loads over the six weeks preparation training period (pooled values) are presented in Table 4.

The majority of the physiological responses showed a significant correlation ($p < 0.001$) with all physical performance indicators, except acceleration. Importantly, Time in HR zone 4+5 showed moderate to large correlations ($p < 0.001$; $0.58 < r < 0.82$) with all physical performance indicators, except acceleration (trivial correlation); average HR (i.e., beat/min or %) showed moderate to large correlations ($p < 0.001$; $0.50 < r < 0.87$) with four physical performance indicators; maximal HR (beats/min) as well as average R-R interval showed moderate to large correlations ($p < 0.001$; $0.51 < r < 0.76$) with two physical performance indicators. However, maximum R-R interval and HRV showed only trivial ($p < 0.001$; $0.18 < r < 0.28$) or non-significant correlation ($r > 0.5$) with the physical performance indicators. It should be also noted that training load was significantly correlated with all physical performance

indicators and physiological responses with $p < 0.001$ and $r > 0.5$ in the majority of these correlations. However, the correlation between RPE of the previous day and the majority of the physical performance and physiological responses were only trivial to small ($p < 0.001$; $0.5 < r < 0.82$). Muscle status showed also trivial correlations ($p < 0.001$; $0.5 < r < 0.82$) or no-significant correlation ($r > 0.5$) with the physical performances and physiological responses over the six weeks training period.

DISCUSSION

The aim of this study was to examine the effects of a six-week preparatory training on physical performance and physiological adaptations in junior soccer players. Furthermore, it was investigated whether relationships existed between external and internal loads and between objective and subjective internal loads in professional youth soccer players. The main findings included significant increases in the majority of physical performance indicators, and a non-significant trend towards improvements in training load, muscle status and all physiological responses parameters. Furthermore, significant correlations were found between the majority of external load parameters (i.e., performance indicators) and objective (i.e., physiological responses) and subjective (i.e., RPE) internal load

TABLE 4. Correlation between external and internal loads when considering pooled values

	Training Load, muscle status and RPE					Physiological Response						
	Variables	Training load	Muscle status	RPE of the previous day	Maximal HR beats/min	Maximal HR %	Average HR beats/min	Average HR %	Average RR interval	Maximum RR interval	HRV	Time in heart rate zone 4+5
Physical performance	Sprint score	p < 0.001; r = 0.686	p = 0.007; r = -0.176	P < 0.001; r = -0.379	p < 0.001, r = 0.537	p < 0.001; r = 0.517	p < 0.001; r = 0.518	p < 0.001; r = 0.5	p < 0.001; r = -0.464	NS	p = 0.007; r = -0.175	p < 0.001; r = 0.677
	Acceleration score	p < 0.001; r = 0.435	NS	NS	NS	NS	NS	NS	NS	p < 0.001, r = 0.266	NS	p < 0.001; r = 0.281
	Total distance	p < 0.001; r = 0.834	p = 0.012; r = -0.165	P < 0.001; r = -0.245	p < 0.001, r = 0.509	p < 0.001; r = 0.517	p < 0.001; r = 0.536	p < 0.001; r = 0.541	p < 0.001; r = -0.491	p < 0.001; r = 0.261	p < 0.001; r = -0.227	p < 0.001; r = 0.818
	Distance/min	p < 0.001; r = 0.726	NS	p = 0.002; r = -0.198	p < 0.001, r = 0.341	p < 0.001; r = 0.348	p < 0.001; r = 0.354	p < 0.001; r = 0.351	p < 0.001; r = -0.307	p < 0.001; r = 0.253	p < 0.001; r = -0.247	p < 0.001; r = 0.645
	Maximum speed	p < 0.001; r = 0.603	NS	p = 0.009; r = -0.17	p < 0.001, r = 0.443	p < 0.001; r = 0.429	p < 0.001; r = 0.569	p < 0.001; r = 0.56	p < 0.001; r = -0.576	NS	p = 0.001; r = -0.209	p < 0.001; r = 0.66
	Average speed	p < 0.001; r = 0.535	NS	P < 0.001; r = -0.217	p < 0.001, r = 0.471	p < 0.001; r = 0.491	p < 0.001; r = 0.871	p < 0.001; r = 0.83	p < 0.001; r = -0.761	NS	p < 0.001; r = -0.276	p < 0.001; r = 0.743
	Duration	p < 0.001; r = 0.458	NS	p = 0.016; r = -0.158	p < 0.001, r = 0.389	p < 0.001; r = 0.412	p < 0.001; r = 0.493	p < 0.001; r = 0.498	p < 0.001; r = -0.504	NS	NS	p < 0.001; r = 0.579
Training load	1	p = 0.01; r = -0.169	p < 0.001; r = -0.246	p < 0.001, r = 0.637	p < 0.001; r = 0.637	p < 0.001; r = 0.689	p < 0.001; r = 0.697	p < 0.001; r = -0.654	p < 0.001; r = 0.247	p < 0.001; r = -0.234	p < 0.001; r = 0.925	
Muscle status	p = 0.01; r = -0.169	1	p < 0.001; r = 0.563	p = 0.014 r = -0.16	p = 0.027; r = -0.145	p = 0.004; r = -0.189	p = 0.006; r = -0.18	p = 0.005; r = 0.185	NS	NS	p = 0.002; r = -0.202	
RPE of the previous day	p < 0.001; r = -0.246	p < 0.001; r = 0.563	1	p = 0.004 r = -0.189	p = 0.008; r = -0.174	p < 0.001; r = -0.233	p < 0.001; r = -0.225	p < 0.001; r = 0.241	NS	p < 0.001; r = 0.221	p < 0.001; r = -0.255	

parameters and training load. The highest number of moderate-large correlations were registered between performance indicators and the time in HR zone 4+5, average HR, maximal HR, average R-R interval and training load.

Improvements in the majority of physical performance parameters (i.e., sprints, acceleration, total distance and max speed) following the six-week preparation training program are in line with previous findings of Lee and Joo [32] and Asadi et al. [33], who reported improvements in fitness levels and/or sprint ability after eight and six weeks, respectively during preseason training in youth soccer players. Ehrmann et al. [34] found an increase in distance/min (an indicator of workload intensity [35]) was associated with an increased risk of injury. Therefore, it can be assumed that the present preparation training program did not generate an increased risk of injury to the players as the distance/min did not increase significantly. Additionally, the higher values of maximum speed, sprints and accelerations during the POST-test compared to the PRE-test session, indicates the youth soccer players were able to perform more soccer-specific maximal actions following the six-week training program. As the average speed remained significantly unchanged from PRE- to POST-test session, more slower actions must have taken place to compensate for these maximal actions indicating that youth soccer players may adopt more intermittent-based training following the six-week preparation training period.

Regarding the physiological responses, it is well known that a decrease in HR values (i.e., maximum and average HR), and an increase in HRV related parameters, (i.e., HRV and average and maximum R-R intervals), in response to similar training session following a training period, is considered as beneficial cardiac adaptation [30]. Present results indicated a tendency of (i) decrease in average HR and time in heart zone 4+5, and (ii) increase in maximal HR, average and maximal R-R interval and HRV, following the six weeks training program. These findings suggest six weeks of preparatory training may produce slight cardiac adaptations, except for the maximal HR, in the youth soccer players. These results are consistent with previous studies reporting that regular soccer training in the form of small games two to three times a week leads to significant cardiovascular adaptations, regardless of the participants training level, gender, and age [36]. School-based ten-week intervention in the form of small-sided, intermediate-level soccer training also led to structural and functional cardiac adaptations in pre-adolescent boys and girls [37].

The absence of significant improvements in the majority of the physiological responses following the present six weeks training program can be explained by the low responsiveness rate of the entire teams players. Our results indicate that, for all physiological responses, the responsiveness rate to the training adaptations did not exceed 66.7% (i.e., 66.7% for average HR and HRV adaptation, 55.6% for maximal and average R-R interval and only 22.2% for maximal HR); therefore, no significant changes were found for the whole team. However, looking at the responsiveness rate for total distance adaptation, we found a higher rate of nearly 89% and

significant improvements for the entire team following the training program. These findings indicate youth soccer players did not adapt similarly, especially in terms of physiological responses, to the preparation training program. This suggests some of them may have experienced undertraining and/ or suboptimal conditioning due to imbalances in loads and recovery [38]. The content of future training programs should be more individualised and/or differentiated to increase the responsiveness rate and generate significant physiological improvement at the team level. This can be achieved by measuring individual changes in fitness and fatigue markers, which in turn allows quantification of individual response and adaptation to training. This will allow coaches to better understand the impact of programmed loads on players and identify personalized tolerance thresholds for each player [39]. Additionally, it seems imperative to monitor the training load that the athlete experiences during each training session to support training individualisation and avoid incorrectly dosed training load (undertraining or overtraining) [40]. Training monitoring allows the coach to compare planning and achievements and is specific to the athletes age, sex, and performance level [6]. Furthermore, training monitoring is understood as the visualisation and objectification of a training process with the help of suitable parameters and technical instruments [6]. In this context, and in order to determine the most suitable internal loads parameters for the monitoring process, the present study investigated also the relationship between performance indicators and a number of objectives and subjective internal training load parameters and the training load.

Overall, results showed significant correlations between the majority of the physical performance indicators and both objective (HR and HRV related parameters) and subjective (i.e., muscle status and RPE) internal training load parameters in youth soccer players. These findings are consistent with previous studies in professional soccer players showing that external load parameters such as total distance, low-, high- and very-high running distances and times [15], frequency of efforts at high speed [14], and various HR based training loads correlate significantly with RPE [4].

This suggests the highest number of moderate to large correlations were registered between performance indicators variables and the time in HR zone 4+5, average and maximal HR, average R-R interval, and training load. Taking into consideration that successful training monitoring should be very specific to the athlete's performance level [6], these findings indicate HR zone 4+5, average and maximal HR, and average R-R interval as most suitable internal load parameters and training load itself for optimal monitoring process. Monitoring these variables may help the coach to implement correct load management, and reduce the risk of under- or over-training, as well as the risk of injury.

Previous studies also reported significant correlations between objective and subjective internal loads in professional soccer players [4, 15, 40]. Results from this study confirm this relationship in youth soccer players and showed that the majority of the HR and

HRV related parameters were significantly correlated with muscle status and RPE. However, these correlations were only trivial to small with muscle status and RPE of the previous status. The present findings also further suggest a relationship between objective internal loads and training load in youth soccer players. These results identify training load as a potentially significant parameters to provide good information about the status of youth soccer players during the monitoring process.

In summary, both external and internal (objective and subjective) parameters and training load should likely be considered for training monitoring and individualisation of youth soccer players in order to optimise training planning, physiological adaptation and physical performance of the whole team.

Strengths and limitations

The present study is the first to assess the relationships between (i) external and internal loads and (ii) objective and subjective internal loads in professional youth soccer during the pre-conditioning phase. However, there are several limitations warranting further discussion. First, the limited sample size and inclusion of only one age group (16 years old) may limit generalization of the present study. Second, the experimentation period was limited to the preparation phase of the season and only data of male youth soccer players were collected. Therefore, future studies should investigate larger samples size from both sexes and from different ages (15–18 years old) during different periods of the season (or the whole season) to draw

more finite conclusions. Additionally, several methods have been proposed to analyse responsiveness rate to training program, but there is no consensus on which should be considered the gold standard. Thus, our findings concerning inter-individual variability should be interpreted considering this concept.

CONCLUSIONS

In conclusion, these results suggest youth soccer players do not adapt similarly, especially in terms of physiological responses, to the six-week preparation training program. Therefore, the content of future training programs may require more individualization and/or differentiation to increase the responsiveness rate and generate significant physiological improvement in the whole soccer team. Additionally, when using the polar system, the time in HR zone 4+5, followed by training load, average HR and then maximal HR and average R-R interval may be considered an important monitoring variable in youth soccer players. Future research evaluating expanded sample sizes and sexes are required to confirm these findings.

Competing interest statement

All authors declare no competing interest.

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How weekly monitoring variables influence players' and teams' match performance in elite futsal players

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ABSTRACT: This study aimed to investigate how weekly training load constrains the performance of players and teams in official futsal competitions. Data from a professional male team were collected during two seasons (46 weeks). The applied monitoring system analysed the training load (as measured by session perceived exertion, sRPE), the total recovery status (TQR), the well-being score (WBs) and the variability of neuromuscular performance during each week (CMJ-cv). In addition, the performance was assessed for all the matches. A path analysis model was performed to test the associations across variables. Results from the path analysis model revealed that it explains 31% of the teams' performance. In general, the results show that previous team performance has no significant effects on the training week. A significant negative relationship was found between CMJ-cv and match performance ($\beta = -.34$; CI95% $-.359$ to $-.070$), as well as a significant negative relationship between players' match performance and the team's match performance ($\beta = -.55$; CI95% $-.292$ to $.740$). Regarding indirect effects, only a negative association between CMJ-cv and team match performance via players' match performance ($\beta = -.19$; CI95% $-.342$ to $-.049$) was identified. The small variation of the weekly CMJ (CMJ-cv) seems to be a key variable to monitor and explain both player and team performance. Based on this model, and only looking at the physical variables, it was possible to explain 31% of the team's performance. Longitudinal and multi-team studies should be conducted to integrate other technical, tactical and psychological variables that allow the level of understanding of players' and teams' performance to be improved.

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INTRODUCTION

In team sports, the main purpose of the training process is to choose and manage the stimulus that optimize the player/team performance for competition, i.e. allow the players to start the competition with high levels of fitness, motivation, cognitive capacities and a low level of fatigue [1].

In elite futsal, the competition phase usually runs for 9–10 months, with official matches played almost every week and sometimes twice a week [2]. For this purpose, it is important to define an athlete monitoring system that ensures a balance between training load (the product of type, volume and intensity of training), recovery status (individual athlete's response to that load) and readiness for competition [1, 3, 4].

In recent years, the development of monitoring systems in sport has occurred due to the evolution and availability of wearable

technologies. These technologies make it possible, for example, to track and register internal and external load or even the positional relations between players using the Global Positioning System for outdoor modalities or, more recently, ultra-wideband technology for indoor modalities [5–7].

However, for some athletes/teams/squads, insufficient resources can be a major reason for not developing and implementing a monitoring system [8]. Based on that, friendly and understandable common tools [8, 9], which include subjective well-being questionnaires (mood, stress, fatigue, soreness and sleep) (WBs) and their derivatives, such as session rated perceived exertion (sRPE) and the total quality recovery (TQR), have been frequently used in team sports [10].

In an attempt to build the relationship between training load and WBs, some authors revealed that the muscle soreness and fatigue

measured with a well-being questionnaire were moderately and inversely correlated with sRPE [11]. In line with that, in another study, the authors found that higher TQR seems to be related to better self-reported sleep quality [12].

Despite the reliability and informative value of subjective measures of training load and well-being [13], these should be combined with more precise and objective variables to ensure a balance between athlete perception and actual performance capacity [4].

Vertical jump height is one of the most reliable measures to quantify the athletic performance and the training-related fatigue in elite players [14, 15].

However, more than analysing physical and wellness data in isolation, there is a need to contextualize the data for a clear understanding of the results [16]. For instance, opponent standard and match outcome seem to affect weekly training load values. When looking particularly to match outcomes in elite soccer, it was revealed that players perceived a higher training load after a defeat or a draw compared to a win [17, 18]. Despite the particularities of each sport, in elite Australian football teams, it was noted that a balance on training load during the week increases the chances of teams winning the match [19]. However, while this relationship is interesting, there is a paucity of research examining the weekly training-performance relationship, particularly in futsal. In fact, in opposition to previous research, coaches always try to integrate the analysis of weekly training load with match performance indicators to improve the ability to understand the relationship between the process and the result [16].

Match performance indicators can be defined as a selection and combination of variables (e.g., passes, shots, goals, dribbles, interceptions, tackles) that characterizes individual or team performance helping to explain the team's match performance [20]. Studies in

other team sports suggest that the match performance indicators are fundamental for coaches to adjust the systems and strategies of play to the next matches and to cogitate about next week's programme [21]. Previous research has revealed high reliability of such variables and a relationship with match outcome and teams' level [22] or even with match external load [23].

The aim of the current study was to investigate how weekly training load constrains players' and teams' match performance through the influence of previous team performance. It was expected to observe: i) an effect of previous team performance on weekly training load; ii) a negative relationship between session rated perceived exertion (sRPE), total quality recovery (TQR) and well-being score (WBs) with countermovement jump variability (CMJ-cv); iii) a negative effect of CMJ-cv on players' and teams' match performance.

MATERIALS AND METHODS

Procedures

An observational descriptive study was carried out during the competitive phase of 2018–2019 and 2019–2020 seasons. Data from 230 training sessions, and from 46 microcycles, were collected, with only one match per week and 5 days of training session prior to the match. The matches included 23 wins, 5 draws and 18 losses. The weekly training programme was planned entirely by the team's coaching staff and aimed to develop an integrated content (i.e., tactical, technical and physical factors were amalgamated) throughout the microcycle, which was divided into 3 physical periodization goals: Recovery (MD-5 [i.e., 5 days before a match]), Acquisition (MD-4/MD-3 [i.e., 4 and 3 days before a match]) and Tapering (MD-2/MD-1 [i.e., 2 and 1 days before a match]). As recovery strategies, all players performed a 5-minute cold-water immersion every MD-4 and MD-2 throughout the in-season.

TABLE 1. Tracking weekly training variables of athlete monitoring system

Match Day	MD-5		MD-4		MD-3		MD-2		MD-1		Game
Physical Intention	Recovery		Acquisition		Acquisition		Tapering		Tapering		Competition
Monitoring Tools	Before	After	Before	After	Before	After	Before	After	Before	After	After
TQR	x		x		x		x		x		
sRPE		x		x		x		x		x	
WBs			x				x				
CMJ			x				x				
PMP											x
TMP											x

TQR – Total Quality Recovery; s-RPE – Session Rated Perceived Exertion; WBs – Well-being Score; CMJ – Countermovement Jump; PMP – Player's Match Performance; TMP – Team Match Performance

Participants and Setting

Data were collected from one single team, comprising 19 professional male futsal players (age: 24.5 ± 3.8 years; height: 173.6 ± 5.4 cm; weight: 70.3 ± 7.6 kg) who participated in the Portuguese first futsal league (Liga Placard). Of the 15 players who started the 2018–19 season, 11 remained in 2019–20, and 5 new players were part of the new season.

For players to be included in the data analysis, they had to meet the following criteria: (i) have participated in more than 80% of the weekly training sessions, and (ii) have started each week with medical clearance to compete.

The experimental procedures used in this study were in accordance with the Declaration of Helsinki and were approved by the local Ethics and Scientific Committee of University of Beira Interior (CE-UBI-Pj-2018-029). All players in the sample were familiar with the club's standard monitoring routine. The club and players provided written informed consent to allow the use of data.

Measures

The monitoring tools included the daily analysis of the training load through sRPE and the recovery status using the TQR scale. Hooper's Index questionnaire was used to record WBs and CMJ was used as a physical performance test and fatigue control measure, both performed only twice a week (see Table 1). All these data were collected all training sessions over the two in-seasons. Player match performance and team match performance were collected from all the matches played over the two seasons.

Session Perceived Exertion

The training load was quantified by the sRPE method. This method has been validated for monitoring internal training load in futsal [24].

Thirty minutes after the end of each daily training session (6 pm – 7 pm) athletes were presented with 10-point RPE scale and answered the question, "How intense was the training session?" using a visual analogue scale in which 0 means "not at all" and 10 "maximum effort". The sRPE was calculated by multiplying the reported RPE score and the total time of the session, in minutes, which represents the overall load of the session in terms of AU. Higher values of sRPE correspond to higher values of training load.

State of Recovery

To assess the state of recovery, the players answered the TQR scale. Before the start of the training session, the athletes answered the question "How recovered do you feel?" on a scale of 6–20, with 6 meaning being rested and 20 meaning extremely good recovery. The weekly average TQR score for each athlete was calculated. Higher values of TQR represent good levels of recovery during the week.

Well-being Score

Individual responses to training demands were measured by the well-being questionnaire which was administered every morning

(9 am – 10 am) twice in the week (MD-4 and MD-2). Players completed a short questionnaire on their smartphone using a Google doc form. The questionnaire had 5 separate aspects of player well-being [25]. These were: 1) How sore do your muscles feel today? 2) How fatigued do you feel today? 3) How well did you sleep last night? 4) How is your mood today? 5) How stressed do you feel today? Each question was scored using a 1–5 Likert scale with 1 representing a low score and 5 a high score. These responses were then converted into a global WBs (%).

Neuromuscular Performance

In order to monitor fatigue and neuromuscular performance, jump height was measured during a CMJ test (Optojump; Microgate, Bolzano, Italy) performed twice a week: MD-4 and MD-2. The test was performed before the training session in a randomized order. A standard warm up programme was completed prior to the test consisting of 10 minutes on a stationary bike followed by dynamic stretching and 3 trial jumps with increased intensity. Finally, they performed 3 jumps with approximately 45–60 seconds recovery between them. All jumps were performed with the players in the tall standing position, with both feet placed hip to shoulder apart and hands akimbo. The mean value of the three attempts of CMJ in the two evaluation moments of the week was used to calculate the coefficient variation of the jump height (CMJ-cv). The CMJ-cv expresses the variations on athletic performance of players over the week, with lower values representing stable and adjustable weekly training load to players' athletic performance.

Players' Match Performance

The Instat Index (Instat, Moscow, Russia) calculates a match performance indicator for each player. It is a unique parameter that provides an assessment of a player's match performance based on the combination of 12 to 14 performance variables, with a higher numerical value indicating better performance [23]. It is created by an automatic algorithm that considers the player's contribution to the team's success and the significance of their actions. The rating is created automatically, and each parameter has a factor that changes depending on the number of actions and events in the match.

Team Match Performance

All official matches that allowed one week of preparation were considered, and for the analysis, the number of points achieved at the end of the match according to the result was considered. That is, 3 points correspond to victory, 1 point to a draw and 0 to defeat.

Statistical Analysis

Descriptive statistics including means, range values and standard deviation, as well as bivariate correlations, were calculated for variables under analysis. In addition, a path analysis model via the maximum likelihood (ML) estimator method in AMOS 23.0 was performed to test the associations across studied variables [26].

Bootstrap resampling (1000 samples) via bias-corrected 95% confidence intervals (CI) was used to assess the significance of the direct and indirect effects. An effect is considered significant (at $\leq .05$) if its 95% CI does not include zero [27, 28]. Effect sizes were evaluated as trivial (0–0.19), small (0.20–0.49), medium (0.50–0.79), and large (0.80 and greater) [29]. The model fit was assessed through the following traditional goodness-of-fit indexes: comparative fit index (CFI); Tucker-Lewis index (TLI); standardized root mean square residual and root mean square error of approximation (RMSEA) and its respective confidence interval (90%). For these indexes, the suggestions of several authors [26, 30, 31] were adopted: CFI and TLI $\geq .90$; SRMR and RMSEA $\leq .08$.

RESULTS

Preliminary Analysis

The inspection of the data revealed that missing values were less than .1% of the sample considered in the present study, and consequently the full information maximum likelihood estimation (FIML) was considered for analysis [32]. Additionally, no outliers (univariate and multivariate) were identified. Skewness and kurtosis values were within cut off values revealing no violation from univariate data distribution. Nevertheless, Mardia's coefficient for multivariate kurtosis exceeds the recommended value (Byrne, 2016). Therefore, a Bollen-Stine bootstrap (2000) was performed for further analysis. Finally, the collinearity diagnosis was checked via the variance inflation factor (VIF) and a tolerance test assuming values less than 10 for VIF and greater than .01 for tolerance test. Therefore, the results showed

that both in VIF and tolerance tests scores were below 10 and above .1 respectively, ensuring the appropriate conditions to test the regression model [31].

Descriptive Statistics

Table 1 presents the average values and respective standard deviation of the weekly training variables as well as the bivariate correlations between them. The results revealed that team match performance has a significant positive correlation with the player's match performance ($r = .55^{**}$) and in turn, the player's match performance is significantly influenced by the CMJ-cv ($r = -.33^{*}$).

All the other variables did not reveal significant correlations and can be found in Table 2.

Path Analysis

The test of path analysis model included previous team performance, sRPE, TQR, WBs, CMJ-cv, players' match performance and team match performance. The results show that the proposed model fit the data ($\chi^2 = 14.71$ (16); SRMR = .080; B-Sp = .473; RMSEA = .053 [90%CI = .000, .161]; TLI = .909; CFI = .929). Considering direct and indirect effects the proposed model explains 31% of match players' and team performance. The standardized direct effects of each path and sample are displayed in Figure 1. The observed effects varied between trivial and medium. Regarding indirect effects, only a negative association between CMJ-cv and team match performance via player's match performance ($\beta = -.19$; CI95% $-.342$ to $-.049$) was observed.

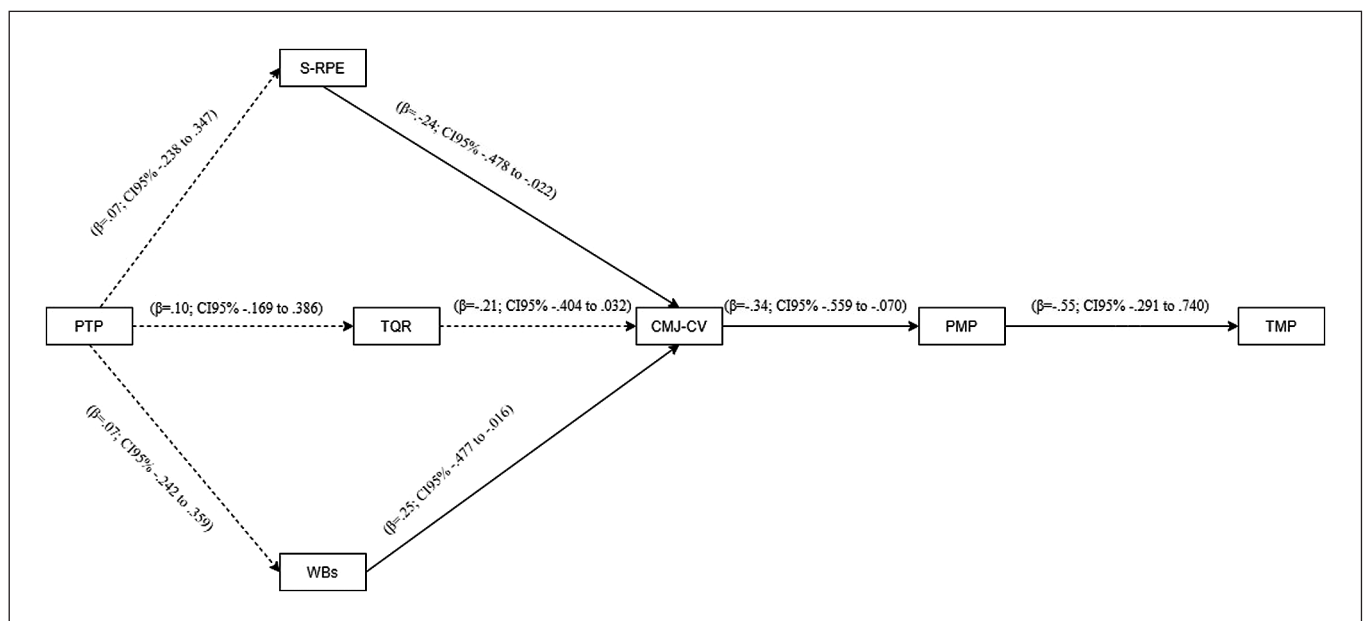


FIG. 1. Performance explanatory model. Standardized direct effects of each path and sample

Note: PTP = previous team performance; S-RPE = session rated perceived exertion; TQR = total quality recovery; WBs = well-being score; CMJ-cv = coefficient variation of countermovement jump; PMP = player match performance; TMP = team match performance.

TABLE 2. Descriptive statistics and bivariate correlations

Variables	M	SD	Range	1	2	3	4	5	6	7
1. PTP	1.45	1.42	0–3	1	-	-	-	-	-	-
2. sRPE	371.08	48.04	254.46–463.03	.07	1	-	-	-	-	-
3. TQR	15.70	.91	14.40–18.81	.10	-.10	1	-	-	-	-
4. WBs	67.45	4.72	59.33–77.56	.07	-.25	.17	1	-	-	-
5. CMJ-cv	.14	.06	.06–.34	.15	-.16	-.23	-.22	1	-	-
6. PMP	220.12	31.84	160.50–279.77	-.01	.09	.13	.12	-.33*	1	-
7. TMP	1.61	1.42	0–3	.23	.10	-.08	-.03	-.02	.55**	1

Note. M = Mean; SD = Standard deviation; PTP = Previous Team Performance; sRPE = Session Rated Perceived Exertion; WBs = Well-being Score; CMJ-cv = Countermovement jump – coefficient variation; PMP = Player's Match Performance; TMP = Team Match Performance * $p < 0.05$; ** $p < 0.01$.

DISCUSSION

The aim of this study was to investigate how the context defined by the match outcome of the previous match influences the weekly training load and well-being, and its contribution to explain players' and team match performance of the following match. The proposed model for the training monitoring process explained 31% of team match performance. Bearing this in mind and knowing that success in futsal is the expression of a complex mix of technical, tactical, physical and mental factors [21], as well as all the factors that can affect the players' performance or the success of the teams, the 31% that explains the team match performance appears to be a small, but considerable percentage for management by all the stakeholders in the training process.

The current main findings show no direct relationship between previous team performance and the following week's training, and WBs variables. In addition, CMJ-cv proved to be a key variable to explain players' and team match performance. To explain this finding, low values of CMJ-cv were related to higher individual and successful team match performance. Interestingly, higher values of weekly load and higher values of WBs were related to lower CMJ-cv.

Previous research in association football revealed a significant increase in perceived training load when a negative result (defeat or draw) occurred in previous matches [17]. Curiously, another study, with football teams, revealed greater total distance covered by players during training sessions after a win compared to a draw or defeat [18]. Also, with football it seems that when players lose a match, mood and stress are negatively affected, suggesting that the disappointment of losing a match could persist for several days [33]. Despite this, we find it interesting that regardless of the match result, futsal players manage to maintain their external load level [34].

In contrast to previous studies with football, and despite the differences between sports, our results did not reveal any significant relationship between the previous team performance and the

weekly training variables (sRPE, TQR and WBs) considered. Thus, it seems that over the two seasons, internal weekly training load in futsal is not sensitive to previous team performance. These results, in comparison to previous results in football, may be explained by the fact that in futsal there are unlimited substitutions, and by the characteristics of training sessions mostly adopted in futsal, with the goal of maintaining the regularity in training load over weeks [7, 35]. Future studies should take into account the cumulative effect of loads over the weeks and be developed not only considering the match result, but also the subsequent match conditions and even the performance of players during such matches. Also, the analysis method should consider a more individualized approach that accounts for individual variability in time of play and other individual characteristics to further explain individuals' variations in perception of the weekly training load [6].

The analysis of the weekly training load using subjective (sRPE, TQR and WBs) and objective (CMJ) measures [4, 14, 36] allows one to monitor variations in players' physical performance and the state of readiness for competition.

While subjective measures contributed to evaluating the response of players to the session training load in relation to rest strategies and its influence on the general wellbeing, the objective evaluation of CMJ provided a reliable quantification of athletic performance and training-related fatigue of players [14, 36]. In line with that, our results revealed a significant negative relationship of sRPE and WBs with the CMJ-cv (the higher the sRPE and WBs values, the lower the weekly CMJ-cv).

Thus, despite a lack of correlation between sRPE and WBs, it seems that higher training load combined with higher wellbeing states could promote lower variation in CMJ and consequently ensures higher performance and readiness for competition [37–39]. These findings are in agreement with previous research which suggested that the monitoring process should account for variations

in training load and in well-being responses [40]. In fact, based on our results, coaches cannot only think that the high sRPE is better. The range (~254 to ~463 AU) and the mean values (~371 AU) of the daily sRPE variable were in line with the optimal range values for the daily training load for professional female futsal players [41]. Thus, the higher sRPE needs to ensure a balance between training load, recovery status, and WBs [4]. A correct balance of the training load is related to the greater probability for the success in the match outcome [19]. This result revealed that the weekly tracking of sRPE and WBs can give coaches the possibility to better manage training load and players' fatigue state and performance readiness.

In this study, the analysis of weekly variations of CMJ (CMJ-cv) was revealed to be a key factor to synthesize balance in weekly training load with implications for players' readiness to compete and to achieve higher individual performances and collective results. In opposition to previous research, in which external and internal load revealed trivial relationships with match statistics [9], the use of CMJ-cv seems to have clearly captured players' readiness for performance.

In line with our results, lower values of CMJ-cv promoted higher players' match performance. This is an interesting finding with clear implications for coaches' intervention. This major finding suggests that correct variation of the training load, recovery status, and WBs during the microcycle [4, 36] allows players to maintain their level of neuromuscular performance and consequently to achieve high performance results in the match.

One of the limitations of the study is the fact that despite having a database from two full seasons, it only considered one team as a sample, which obviously limits the generalizability of the findings. Longitudinal, multi-team studies are therefore required to make more reliable inferences on the effects of individual factors on futsal performance.

CONCLUSIONS

Contextual factors (previous team performance) seem to have no significant influence on monitoring the weekly training programme in futsal. The monitoring system defined by the analysis of the training load (as measured by session perceived exertion, sRPE), recovery status (TQR), players' well-being (WBs) and neuromuscular performance (CMJ-cv) was fundamental to understand players' readiness for competition with implications for their match performance and consequently for the final team result (team match performance). The methodologies we used could be applied to other similar sports to provide novel insights about performance.

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Conflict of interest

The authors declare no conflict of interest.

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The effect of combining HIIT and dry-land training on strength, technique, and 100-m butterfly swimming performance in age-group swimmers: a randomized controlled trial

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ABSTRACT: Combined interventions of pool-based and dry-land workouts are a common practice in swimming training. However, the effects on strength, technique and swimming performance are still not clear. Through a randomized controlled trial study, we investigated the effect of combining high intensity interval training (HIIT) and maximum strength training (MST) on strength, technique and 100-m butterfly swimming performance. Competitive age-group swimmers ($N = 22$, males) were randomly divided into two groups. The experimental group (EG: 14.1 ± 0.3 years old) performed 8 weeks of combined short-moderate HIIT and MST. The control group (CG: 14.5 ± 0.3 years old) subjects performed their usual training. Muscular strength, technique and swimming performance were evaluated before and after 8 weeks. Substantial improvements were observed in maximum muscle strength (mean diff: 22–28%; $p < 0.001$; $d = 3.25$ – 3.61), technique ($p < 0.05$; $d = 0.98$ – 1.96) and 100-m butterfly swimming performance (3.5%; $p = 0.001$; $d = 1.81$) when combining HIIT and MST during 8 weeks. Combining short-moderate HIIT and MST during 8 weeks can enhance maximum muscular strength, technique, and 100-m butterfly swimming performance. Coaches should adjust training programmes accordingly since it could yield important differences in swimming performance during competitions.

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INTRODUCTION

Performance in competitive swimming is a multifactorial phenomenon, i.e., it is determined by a relatively large number of factors (e.g., energetics, technique, anthropometrics) [1–3]. When it comes to improving swimming performance, it is well reported that dry-land workouts including maximum strength training (MST) can improve it [4–5]. Likewise, high intensity interval training (HIIT) workouts can enhance swimming performance [6]. Most swimming-related studies verified the effects of MST and HIIT on swimming performance in an independent manner, and generally in front crawl swimming. Although relevant, it is also necessary to observe this phenomenon in a randomized approach, i.e., by examining the combined effect of MST and HIIT on strength, technique and swimming performance, and also particularly in other swimming techniques (e.g., butterfly).

Combined dry-land workouts and HIIT have been applied in some sports [7–8]. Combining strength workouts (2–6 sets of parallel squats at 80% of one-repetition maximum, 1-RM) and HIIT (8–24 "Tabata intervals" at ~150% of maximal oxygen uptake, O_{2max}) for 6 weeks could improve O_{2max} and performance of parallel squats ($4 \pm 3\%$ and $14 \pm 10\%$, respectively) in highly skilled ice hockey and rugby players [7, 9]. Aspenes et al. [9] suggested that the 1-RM and 400-m front crawl swim performance improved after 11 weeks (16.87% and 1.38%, respectively) when combining HIIT and MST. Eighteen sessions of HIIT over 2 weeks were enough to improve 750-m swim (4%) and 20-km cycling time (8%), and peak oxygen uptake (O_{2peak}) (2%) in adolescent triathletes [10]. Sperlich et al. [6] suggested that 5 weeks of HIIT (2 sessions $\cdot$ week⁻¹) could improve O_{2max} and performance

of 2000-m and (10%, 3%, respectively) in competitive age-group swimmers. In fact, HIIT is an effective training modality for improving endurance quality in numerous sports [6, 10]. HIIT workouts can be categorized based on interval work-bout duration: short HIIT if work bouts are under 30 s, medium HIIT if 30 s to 2 min, and long HIIT if 2 to 4 min [11–12]. However, information on technique adaptation after combining MST and HIIT remains scarce in age-group swimmers, particularly other swimming techniques.

The metabolic power (energy expended per unit of time) is very important in aquatic locomotion [1, 5, 13]. An increase in metabolic power with swimming speed (v) reflects the increase in (total) mechanical power output that muscles need to provide while sustaining that v [1]. Additionally, maximum upper body strength (bench press) and lower body (back squat) explain ~55–65% of the performance in the tethered swimming power, ~50% of swim start performance and 45–62% of 50-m and 100-m front crawl swimming performance [13]. Amaro et al. [14] suggest that the MST stimulus must be characterized by an intensity greater than 80%1-RM, in 2 to 3 sets with 3 to 5 repetitions and a recovery interval between 2 and 5 min. Bench press (BP), leg extension (LE) and back squat (BS) are widely used in dry-land training protocols to improve upper and lower body strength in swimmers [15]. In the same perspective, maximum upper and lower body strength could be determined by 1-RM of bench press (1-RM BP) and 1-RM of leg extension (1-RM LE) [13, 16].

Evidence on the effect of combining strength training (only upper body) and HIIT on front crawl swimming performance is scarce [8]. This reinforces that we need more evidence to understand the effect of combining HIIT and MST (upper and lower body) on swimming performance, particularly in swimming techniques other than front crawl. Through a randomized controlled trial, we verified the effect of 8 weeks of combining HIIT and dry-land training with MST in upper and lower body on changes in muscle strength, technique and butterfly swimming performance. We hypothesized that such an approach would improve maximum muscular strength, technique, and 100-m butterfly swimming performance in competitive age-group swimmers.

MATERIALS AND METHODS

Study design

In this randomized controlled study, twenty-two swimmers were randomly allocated to an experimental group (EG), combining MST and HIIT, and a control group (CG), which performed habitual training. Maximum muscle strength (1-RM BP and 1-RM LE), technique (velocity, stroke rate, stroke length and stroke index) and swimming performance in 100-m butterfly swimming were measured before and after 8 weeks of both training conditions. Swimmers were familiarized during 1 week before the first testing with bench press (BP) and leg extension (LE) repetitions. In addition, swimmers were instructed not to perform any other physical training regimen in terms of speed and strength over the study period. All participants were injury free prior to the preliminary practice.

TABLE 1. Subjects characteristics (mean $\pm$ SD) from experimental (EG) and control (GC) group

	EG (n = 11)	CG (n = 11)
Age (yr-old)	14.1 $\pm$ 0.30	14.5 $\pm$ 0.32
Height (cm)	170 $\pm$ 9.8	171 $\pm$ 8.4
Body mass (kg)	68.74 $\pm$ 4.35	68.08 $\pm$ 3.79
Arm span (cm)	173 $\pm$ 10.2	173 $\pm$ 10.7
Competitive swimming experience (years)	6.43 $\pm$ 0.29	6.34 $\pm$ 0.25
Dry-land experience (years)	3.51 $\pm$ 0.24	3.50 $\pm$ 0.26

Participants

National level age-group swimmers (N = 22, males), specialized in butterfly, volunteered to participate in the current study. They were randomly allocated to an experimental group (EG, N = 11; age: 14.1 $\pm$ 0.30 years; height: 170 $\pm$ 9.8 cm; body mass: 68.7 $\pm$ 4.3 kg) and control group (CG, N = 11; age: 14.5 $\pm$ 0.32 years; height: 171 $\pm$ 8.4 cm; body mass = 68.1 $\pm$ 3.8 kg). An a priori power analysis (G*Power 3.1.9.3) showed that a sample size of 8 was necessary to detect large effects ($d = 1.33$) using a power of 0.8 and alpha of 0.05. The swimmers are specialists in butterfly swimming, with more than 6 years of competitive experience in swimming and 3 years of strength training. Swimmers' parents were informed about the benefits and risks of participating in the current study prior to signing an informed consent form, which was approved by the ethics board of the Higher Institute of Sport and Physical Education of Ksar Said, University of Manouba, Tunisia, in accordance with the Helsinki Declaration. Table 1 presents characteristics of subjects from experimental (EG) and control (GC) groups.

Procedures

Pool-based training and swimming performance tests took place in a 50-m indoor pool with 27.3 and 25.8°C water and air temperatures (respectively), and 64% relative humidity. Dry-land training and strength tests were performed in a bodybuilding room.

Training in the water

The CG subjects were invited to continue their usual programme, characterized by low intensity and high volume (Fig. 1 and Table 2). The EG was invited to perform a training programme with an increase in HIIT volume but lower total volume (Fig. 1 and Table 2) compared the CG [17–18]. The two training programmes were composed of three major training categories:

- (i) *Low-intensity aerobic (LI-Aerobic): warm-up, warm-down, technique exercises and low- to moderate-intensity training (< 70% of maximal heart rate, HR max; e.g. 20 $\times$ 100 m);*

- (ii) *High-intensity aerobic (Hi-Aerobic): High-intensity aerobic training (70–85% HR max; e.g. 5 × 400-m);*
- (iii) *High-intensity interval training (HIIT): short HIIT (volume: < 30 s; e.g. 8 × 50 m) and moderate HIIT (volume: 30 s to 2 min; e.g. 4 × 100 m); Intensity: > 85% HRmax; recovery time between repetitions: ratio 1:1; recovery between sets: 3 min; Table 2 and Fig. 1).*

The HR was recorded during the first 10 s after cessation of the bout using a Polar Team 2 (Finland) [19].

Both training programmes (CG and EG) were performed for 8 weeks (6-sessions · week⁻¹):

- (i) *Intervention Period (IP, 6 weeks): The CG performed 201 km of total training volume and 4.7 km of HIIT volume. The EG performed 105 km of total training volume and 23.6 km of HIIT volume [17–18];*
- (ii) *Taper Period (TP, 2 weeks): Reduction of training volume during the taper period was applied accordingly Mujika et al. [20]. The total training volume and volume of three major training categories (Li-Aerobic, Hi-Aerobic and HIIT) of both groups decreased by 40% in the first and 70% in the second week of TP compared to the last week of IP (week 6). The intensity (workload) remained unchanged for both groups during TP [20].*

Dry-land training

The dry-land programme was applied by experienced strength and conditioning coaches. The CG was invited to continue the usual dry-land training, characterized by general core strength (push-up, abdominal exercises, squat). The EG was invited to perform a dry-land MST programme, including bench press and leg extension exercises (2–5 sets × 3–5 repetitions × 85–95% 1RM) [16, 21]. Volume-load bench press (VL BP) and leg extension (VL LE) were determined

according to the following equation, i.e. by multiplying the load lifted by the repetitions completed in a given set [22]:

$$\text{Volume-load} = \text{Number of sets} \cdot \text{Number of repetitions} \cdot \% 1\text{RM}$$

where the 1RM of each subject was measured at pre-test. The total volume load (TVL) was then calculated by the sum of VL BP and VL LE (Fig. 2).

The two dry-land training programmes are characterized by two periods:

- (i) *6 weeks of IP (2 sessions · week⁻¹): the EG performed 9360.9 ± 735.08 kg of TVL (4628.7 ± 366.87 kg [VL BP] + 4732.2 ± 401.49 kg [VL LE]) with intensity fixed between 85*

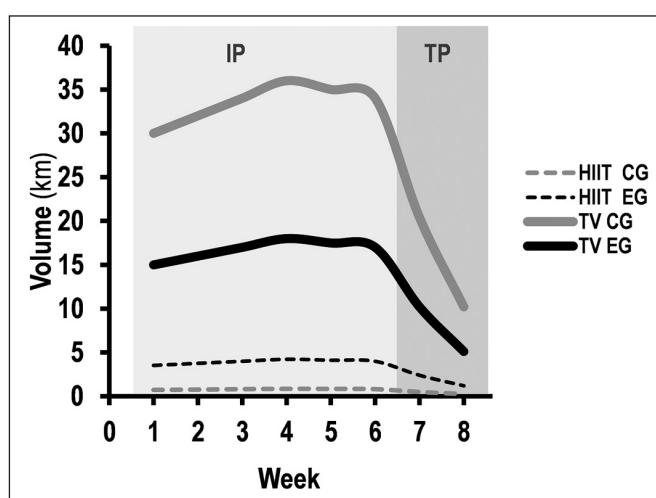


FIG. 1. HIIT and training volume over 8 weeks of pool based training for both groups (CG and EG). IP: intervention period; TP: taper period; HIIT: high intensity interval training with intensity > 85% HRmax.

TABLE 2. Detailed description of 8-weeks for the Control Group (GC) and the Experimental Group (EG)

		Intervention period	Taper period	W1	W2	W3	W4	W5	W6	W7	W8
Total Training Volume (km)	CG	201.0	30.6	30.0	32.0	34.0	36.0	35.0	34.0	20.4	10.2
	EG	105.0	15.3	15.0	16.0	17.0	18.0	17.5	17.0	10.2	5.1
Li-Aerobic (km)	CG	187.4	28.5	28.0	29.8	31.7	33.6	32.6	31.7	19.0	9.5
	EG	70.9	10.8	10.6	11.3	12.0	12.7	12.4	12.0	7.2	3.6
Hi-Aerobic (km)	CG	10.4	1.4	1.3	1.4	1.5	1.6	1.5	1.5	0.9	0.5
	EG	5.9	0.9	0.9	0.9	1.0	1.1	1.0	1.0	0.6	0.3
HIIT (km)	CG	4.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.5	0.2
	EG	23.7	3.6	3.5	3.8	4.0	4.2	4.1	4.0	2.4	1.2

W: week; Li-Aerobic: low intensity-Aerobic with intensity < 70% HRmax; Hi-Aerobic: high intensity-Aerobic with intensity between 70 to 85% HRmax; HIIT: high intensity interval training with intensity > 85% HRmax.

and 95% 1-RM. The recovery time between sets and exercises ranged from 3 to 5 min. The CG performed general core strength training with volume time (VT) fixed at 75 min and intensity fixed between 70 and 85% HRmax [15–16, 21].

- (ii) 2 weeks of TP (1 session · week⁻¹): Reduction of training volume was accordingly Pritchard et al. [23]. However, for both groups, training volume decreased by 40% in the first week (EG: TVL: 810 ± 65.87 kg = 399.6 ± 31.67 kg [VL BP] + 410.4 ± 35.82 kg [VL LE]; CG: VT: 45 min) and 60% in the second week (TVL: 540 ± 43.91 kg = 266.4 ± 21.12 kg [VL BP] + 273.6 ± 23.88 kg [VL LE]; CG: VT: 30 min) in relation to the last week of the intervention period (week 6). The intensity remained unchanged in both groups during this period [23].

Testing procedure

All the tests were performed within two days (standardized order), with dry-land measurements being taken on the first day and pool-based measurements on the second day.

Muscle strength

The 1-RM protocol started with a standard warm-up where all subjects were invited to cycle during 3 min in an ergocycle, followed by 5 min of general static stretching. Then, subjects performed one set of 8–10 repetitions at 50% of 1-RM (estimated) and one set of 3 repetitions at 70% of 1-RM for both exercises (bench press, BP; and leg extension, LE). During the test, the load was gradually increased (10 to 20%) while the number of repetitions decreased

(2 to 3), with 2 to 4 min of recovery. Then, a small increase in the load (5%), with 2 to 4 min of recovery, was performed to establish the 1-RM for BP and LE. The test ended when the subjects failed to complete the correct movement of the leg extension and of the bench press, and the last successful attempt represents the 1-RM. To maintain a good command of the bench press execution technique, the Smith machine was used during the 1-RM BP test, while the leg extension machine was used during the 1-RM LE test [24]. Two coaches specializing in strength and conditioning controlled all the tests.

Swimming performance

All swimmers completed an 800-m warm-up (600-m low- to moderate-intensity swimming [$< 70\%$ of HR max] and 200-m progressive sprint) prior to completing two maximum trials of 100-m butterfly (with 30 min of rest between trials) [25]. Two experienced timekeepers measured the time of each trial with a stopwatch (SEIKO S120-4030, Japan). The best performance value between both trials was used. Intraclass correlation coefficient (ICC) of the two trials for Pre- and Post-test were 0.99 ($p < 0.001$) and 0.98 ($p < 0.001$), respectively.

Technique variables

A surface video camera, Sony SNC VB 603 (50 Hz, full HD, 1080 p) was used to assess technique variables. The video camera was positioned laterally (5 m above the water and 10 m away from the edge of the pool), within two points to exclude the influence of the turning phase (1st 50 m: between 20 and 40 m, 2nd 50 m: between 70 and 80 m). Data were analysed with Kinovea software (Kinovea 0.9.1; Joan Charmant & Contrib., kinovea.org) [25–26]. The v of each 10 m was measured from the time taken to cover the middle 10 m of the two distances ($v = d \cdot (t_{10\text{-m}})^{-1}$, where $t_{10\text{-m}}$ = time for the 10 m and $d = 10$ m). Stroke rate (SR) was calculated from the time taken to complete three consecutive stroke cycles. Stroke length (SL) was computed from the ratio between v and corresponding SR. Stroke index (SI) was assessed by multiplying v by SL [27–29].

Statistical analyses

The data analyses were performed using IBM SPSS Statistics for Windows, version 20.0 (IBM Corp., Armonk, N.Y., USA). The values are presented as mean $\pm$ SD. Normality was tested with the Kolmogorov-Smirnov test. The intraclass correlation coefficient (ICC) was applied to determine the reliability of the measurements [30]. Repeated measures ANOVA was used to identify the differences between pre- and post-test in the two groups (time factor). The effect size (d) was determined by converting partial eta-squared to Cohen's d [31]. The statistical significance was set at $p \leq 0.05$.

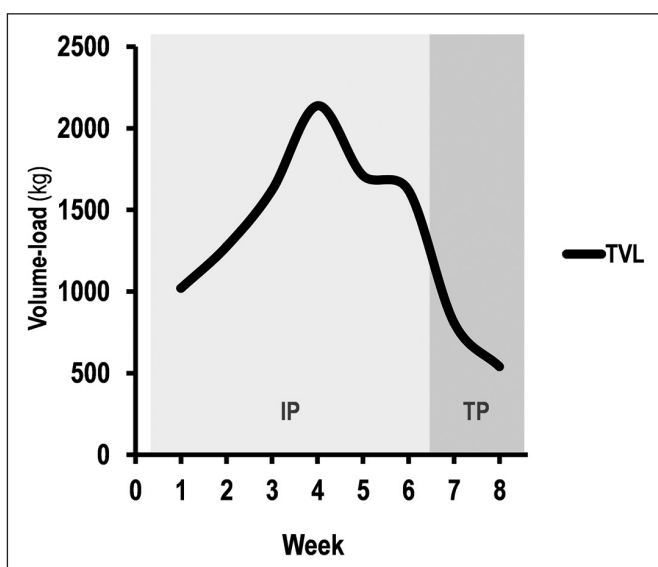


FIG. 2. Total volume load in dry-land training over 8 weeks of maximum strength training for the experimental group. IP: intervention period; TP: taper period; TVL: total volume load with intensity between 85 and 95% 1-RM.

RESULTS

Anthropometric, dry-land and swimming performance variables were similar between the groups at baseline ($p > 0.05$).

Muscle strength

Our results indicate that the 1-RM BP improved after 8 weeks in the EG (22.1%; 95% confidence interval [CI] 10.5 to 5.8 kg; $p < 0.001$; $d = 3.25$; very large). The 1-RM LE also increased after 8 weeks of combined training in the EG (28.2%; 95% confidence interval [CI] 13.5 to 7.9 kg; $p < 0.001$; $d = 3.61$; very large). Dry-land measurement remained unchanged in the CG ($p > 0.05$). The intraclass correlation coefficient of BP and LE test ranged between 0.81 ($p < 0.01$) and 0.72 ($p < 0.01$). All dry-land measurements can be observed in Table 3 and Fig. 3.

Swimming performance and technique

Table 3 shows the swimming performance observed in both groups before and after 8 weeks; however, 100-m butterfly swimming performance improved at post-test only in the EG (3.5%; 95% confidence interval [CI] 1.1 to 3.4 s; $p = 0.001$; $d = 1.81$; large effect). The intraclass correlation coefficient of 100-m butterfly swimming

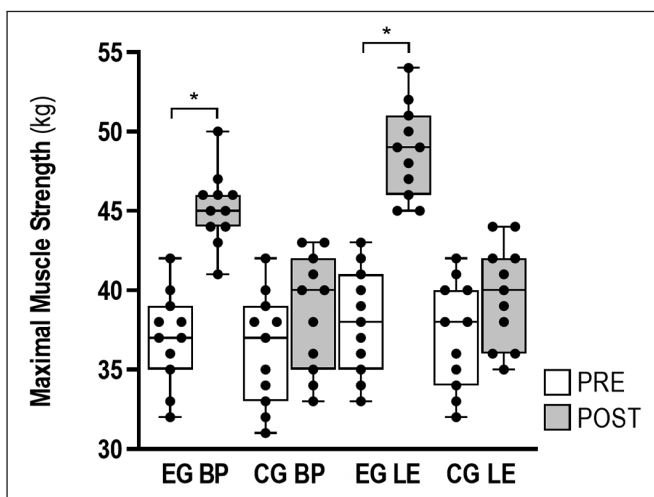


FIG. 3. Box plots displaying the 25th and 75th percentiles, medians, whiskers extending from the minimal to maximal for maximum muscle strength (bench press, BP; and leg extension, LE) in both groups (CG and EG) after 8 weeks of training. (* $p < 0.01$)

TABLE 3. Changes in swimming performance, technique and muscular strength after 8-weeks of training for both groups

Variables	Group	PRE	POST	<i>p</i> -value	Difference [95%CI]; (%Δ)	Effect size (<i>d</i>)
Performance (s)	EG	64.13 ± 1.41	61.85 ± 1.22	0.001	2.28 [1.10 to 3.45]; 3.55%	1.81, large
	CG	64.75 ± 1.55	64.29 ± 1.59	0.504	0.46 [-0.94 to 1.85]; 0.70%	0.02, trivial
v_{1st}^{50-m} ($m \cdot s^{-1}$)	EG	1.76 ± 0.12	1.94 ± 0.09	0.001	-0.18 [-0.27 to -0.09]; 10.17%	1.81, large
	CG	1.76 ± 0.12	1.79 ± 0.12	0.571	-0.03 [-0.14 to 0.08]; 1.65%	0.26, small
SR_{1st}^{50-m} ($cycle \cdot s^{-1}$)	EG	0.74 ± 0.04	0.80 ± 0.05	0.003	-0.06 [-0.10 to -0.03]; 8.65%	1.52, large
	CG	0.74 ± 0.04	0.74 ± 0.04	0.613	-0.01 [-0.04 to 0.03]; 1.35%	0.23, small
SL_{1st}^{50-m} (m)	EG	2.39 ± 0.04	2.43 ± 0.04	0.032	-0.04 [-0.07 to -0.003]; 1.55%	1.03, moderate
	CG	2.38 ± 0.04	2.40 ± 0.03	0.461	-0.01 [-0.04 to 0.020]; 0.42%	0.03, trivial
SI_{1st}^{50-m} ($m^2 \cdot s^{-1}$)	EG	4.22 ± 0.34	4.71 ± 0.14	<0.001	-0.49 [-0.73 to -0.26]; 11.61%	1.96, large
	CG	4.20 ± 0.35	4.29 ± 0.34	0.547	-0.09 [-0.39 to 0.22]; 2.14%	0.27, small
v_{2nd}^{50-m} ($m \cdot s^{-1}$)	EG	1.73 ± 0.11	1.90 ± 0.13	0.003	-0.17 [-0.28 to -0.07]; 9.95%	1.52, large
	CG	1.73 ± 0.11	1.75 ± 0.11	0.683	-0.02 [-0.12 to 0.08]; 1.16%	0.19, trivial
SR_{2nd}^{50-m} ($cycle \cdot s^{-1}$)	EG	0.72 ± 0.03	0.78 ± 0.05	0.003	-0.06 [-0.10 to -0.02]; 8.45%	1.53, large
	CG	0.72 ± 0.03	0.73 ± 0.04	0.462	-0.01 [-0.04 to 0.02]; 1.53%	0.33, small
SL_{2nd}^{50-m} (m)	EG	2.39 ± 0.05	2.43 ± 0.03	0.041	-0.04 [-0.07 to -0.002]; 1.51%	0.98, moderate
	CG	2.40 ± 0.05	2.39 ± 0.04	0.660	0.01 [-0.03 to 0.05]; 0.38%	0.20, small
SI_{2nd}^{50-m} ($m^2 \cdot s^{-1}$)	EG	4.13 ± 0.34	4.62 ± 0.34	0.004	-0.48 [-0.78 to -0.18]; 11.57%	1.47, large
	CG	4.15 ± 0.35	4.18 ± 0.33	0.831	-0.03 [-0.34 to 0.27]; 0.77%	0.09, trivial
1-RM BP (kg)	EG	37.00 ± 2.93	45.18 ± 2.32	<0.001	-8.18 [-10.53 to -5.83]; 22.11%	3.25, very large
	CG	36.27 ± 3.52	38.64 ± 3.64	0.137	-2.36 [-5.55 to 0.82]; 6.52%	0.69, moderate
1-RM LE (kg)	EG	38.00 ± 3.32	48.73 ± 2.90	<0.001	-10.73 [-13.50 to -7.96]; 28.23%	3.61, very large
	CG	37.18 ± 3.40	39.73 ± 3.20	0.086	-2.55 [-5.48 to 0.39]; 6.85%	0.81, moderate

v: swimming speed; SR: stroke rate; SL: stroke length; SI: stroke index; 1-RM: one maximum repetition; BP: bench press; LE: leg extension; EG: Experimental Group; CG: Control Group.

performance was 0.91 ($p = 0.01$). Concerning technique, v improved at the 1st 50 m and at the 2nd 50 m in the EG ($p < 0.01$; $d = 1.52$ to 1.81; large effect). Likewise, SR increased at the two laps in the EG ($p < 0.01$; $d = 1.52$ to 1.53; large effect). SR ($p < 0.05$; $d = 0.98$ to 1.03; moderate effect) and SI ($p < 0.01$; $d = 1.47$ to 1.96; large effect) also improved at the two laps in the EG. Technique remained unchanged in the CG ($p > 0.05$). The intraclass correlation coefficient of all technique variables in the 1st 50 m ranged between 0.83 ($p < 0.01$) and 0.89 ($p < 0.01$) and in the 2nd 50 m ranged between 0.87 ($p < 0.01$) and 0.89 ($p < 0.01$).

DISCUSSION

Training programmes display variable patterns of changes in strength, technique, and other energetic and anthropometric issues [1, 28], i.e. the training stimulus and subsequent adaptations constitute a dynamic and multifactorial process, and [2, 29]. Methodologies and phases in which training are offered to the swimmer can yield large differences in performance outcome [20, 28]. The main aim of our study was to evaluate the effect of combining HIIT and MST on muscular strength and butterfly swimming performance in competitive age-group swimmers. We observed significant improvements in maximum muscle strength, technique and 100-m butterfly swimming performance after 8 weeks.

Effect of training on muscle strength

Combining HIIT and MST during 8 weeks improved maximum upper and lower body strength (1-RM BP = 22.1%; 1-RM LE = 28.2%). Girolod et al. [32] reported that 12 weeks of MST improved elbow flexors in the isometric condition (39.5%) in competitive swimmers. Similarly, Girolod et al. [5] found that 4 weeks of MST optimized the peak torque in the concentric condition at 60° s^{-1} and at 180° s^{-1} (11.2%, 16.9% respectively) in national level competitive swimmers. In other context, Amaro et al. [14] showed that training with 2–3 sets and 3–5 repetitions with intensity between 80 and 90% of 1-RM was beneficial to improve muscular strength. Recently, Kubo et al. [4] reported that 10 weeks of two different doses of MST, MST with higher load–lower repetition (4 repetitions $\cdot$ 7 sets) and MST with intermediate load–intermediate repetition (8 repetitions $\cdot$ 4 sets), improved the 1-RM BP (10 to 29.5%) in healthy men. Our study is in line with previous studies, linking dry-land training to swimming performance gain. The taper period is also essential for adaptation to stimuli, transferring strength gains to propulsive swimming actions [16]. Pritchard et al. [23] suggested that it is necessary to develop a taper period after an MST programme for maximal muscular strength gains. It must range from one to four weeks, be characterized by a decrease in the training load by 30–70% or reduced training frequency, preserving or slightly increasing intensity.

Effect of training on technique and swimming performance

Swimming technique improved during the 1st 50 m (1.55% to 11.61%) and 2nd 50 m (1.51% to 11.57%). This improvement

could be due to the improvement in maximum upper and lower body strength. However, Strass [21] found that 6 weeks of MST could improve the velocity of 25 m and 50 m in front crawl (1.3%; 2.1% respectively) in competitive swimmers. On the other hand, our results are in contrast with other studies that have shown that the HIIT programme does not improve kinematic variables in competitive swimmers [18–33]. The choice of the types of HIIT and the length of the intervention period in these studies could explain these different results.

The results of this study showed that 100-m butterfly swimming performance improved after 8 weeks with combined training (3.55%). In the same context, Ramos Veliz et al. [34] indicated that 18 weeks of combining training between dry-land training and HIIT could optimize the time of the 20-m maximal sprint swim (2.25%) in water polo players. Studies that integrate training in water regardless of HIIT or high-volume training (HVT) and dry-land workouts remain scarce [3, 16]. However, Pugliese et al. [35] observed that 6 weeks of a HIIT programme with 6000 m of HIIT $\cdot$ week⁻¹ improved the 100-m front crawl (1.2%) in competitive swimmers. Moreover, Sperlich et al. [6] reported improvements in 2000-m front crawl (2.8%) after 5 weeks of a HIIT programme (30 min per session at 92% of personal best time) in healthy competitive young swimmers. The HIIT programme has shown beneficial results in the long distance performance [10, 36]. However, Rosenblat et al. 2019 stated that a workout programme containing 80% of HIIT volume could optimize endurance sport performance.

Concerning the relationship between MST and swimming performance, Keiner et al. [13] revealed that maximum strength in the bench press and squat explained 45–62% of the performance variance in 50- and 100-m swimming performance. Similarly, the effect of the MST programme on swimming performance has been tested by some studies [5, 8]. However, Girolod et al. [5] observed that the MST programme (3 sets $\cdot$ 6 repetitions at 80–90% of 1-RM) with exercises of press pull-up, draw with barbells, abdominal, squat and plyometric jumps, improved the 50-m front crawl performance (2%) in national-level competitive swimmers. Aspenes et al. [8] found that 11 weeks of the MST programme (3 sets $\cdot$ 5 repetitions) performing lat pulldown exercise did not improve the performance of 100-m front crawl in competitive swimmers. Despite some inconsistencies in the literature, training intensity seems to be an important factor for performance improvements in swimming [20], and coaches should be (if they are not yet) aware about it.

However, it is important to acknowledge some shortcomings and potential limitations of our study. The current study is considered primarily applicable to a particular age group of male swimmers at a specific level of competition. Thus, it is necessary for more studies to cover female swimmers and other age categories. Future research in this area could also i) investigate the effects of various training protocols of MST with different doses of load volume (repetitions, sets, intensity); ii) investigate the effects of different types and lengths of a HIIT programme associated with swimming specificity; and

iii) undertake integrated assessments of biomechanics and energetics (e.g. metabolic power, energy cost).

CONCLUSIONS

Combining short-moderate HIIT (pool-based training) and MST in dry-land training workouts (1 or 2 sessions per week) is advantageous to enhance maximum muscle strength, technique, and 100-m butterfly swimming performance after 8 weeks in age-group swimmers. Although combining pool-based and dry-land workouts is

a widespread practice in swimming training, our study provides evidence that combining short-moderate HIIT (pool-based training) and MST in dry-land training workouts is effective, highlighting its applicability for coaches and age-group swimmers. Adjusting training programmes accordingly can yield important improvements in swimming performance.

Conflict of interest

The authors declare no conflict of interest.

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Hamstring muscle architecture and myotonometer measurements in elite professional football players with a prior strained hamstring

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ABSTRACT: The purpose of this study was to compare the fascicle length, angle pennation and mechanical properties of the biceps femoris long head (BFLh) in dominant and non-dominant limbs in previously injured and uninjured professional football players. Fifteen professional football players were recruited to participate in this study. Seven players had suffered a BFLh injury during the previous season. Myotonometry mechanical properties were measured in the proximal, common tendon and distal BFLh using MyotonPRO, and angle pennation and fascicle length were also measured. We observed significantly higher distal BFLh frequency, stiffness, decrement, relaxation and creep than in the common tendon and proximal BFLh. The previously injured players showed significantly higher frequency and stiffness, and lower relaxation and creep in the dominant BFLh than did uninjured players. There were no significant differences between the fascicle length and angle pennation in previously injured and uninjured BFLh. Myotonometric measurement provides a quick and inexpensive way to check the properties of the BFLh in professional football players. Professional football players with previous BFLh injury showed higher intrinsic tension and a poorer capacity to deform than did players with no injury to the BFLh.

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INTRODUCTION

Hamstring strain injury (HSI) is the noncontact injury with the highest incidence in football (soccer) [1], accounting for 12–16% of all injuries. This injury has not shown signs of decrease over the last three decades [2]. The biceps femoris long head (BFLh) is the most commonly injured of the hamstring muscles [3], so there is considerable interest in intrinsic factors that predispose football players to BFLh injury [4]. BFLh injuries usually happen during the late swing phase in high-speed running or sprinting at long muscle lengths, and it has been suggested that relatively long muscle fibres can minimize the risk of injury by presenting less stress per sarcomere for a given muscle-tendon unit strain [5, 6]. Among many other well-documented risk factors [7], increased eccentric strength and alterations in muscle architecture (elongation of the BFLh fascicle) have been proposed as modifiable risk factors with a positive impact on hamstring injury prevention [8, 9]. However, the responses of both muscle architecture and strength to training are probably training status dependent; thus, extrapolating the research findings obtained in semi-professional or amateur football players to highly trained professional football players requires caution [10].

Fascicle length alterations and their impact on BFLh injuries have been investigated by a number of researchers [9, 11]. A previous

article using B-mode ultrasound suggested that professional football players with shorter BFLh fascicles (i.e., < 10.5 cm) have a fourfold greater risk of HSI than players with longer fascicles [9]. Given that a previous HSI has been consistently shown to increase the risk of future injury [11], Timmins et al. showed, using B-mode ultrasound, that a previously injured BFLh consistently has shorter fascicles than the uninjured contralateral limb [12]. However, it is not clear whether these differences in fascicle length are due to the previous injury, or a result of decreased ability to activate the previously injured BFLh [13]. Therefore, analysis of the mechanical properties of the BFLh is needed to address this gap in knowledge. A number of ultrasound methods can be used to assess fascicle lengths. Extended field of view (EFOV) ultrasound has been shown to be superior to static ultrasound in assessing BFLh fascicle length by avoiding extrapolation errors [6]. Therefore, the results of previous studies using B-mode ultrasound should be interpreted with caution.

Examining the mechanical properties of a muscle is important in monitoring the state of the tissue, detection of possible fatigue and for assessing the efficacy of treatment/training interventions [14]. Therefore, reliable and sensitive methods for determining neuromuscular function as well as mechanical muscular properties are

essential in professional football. Coaches at the elite football level are often concerned about the possible risks of invasive and maximal testing during intensive training periods, including fatigue, reduced trainability and/or possible future muscle injury [15]. Consequently, non-invasive measurement methods such as myotonometry are an alternative to monitor muscle mechanical properties objectively and regularly during the season. The MyotonPRO (Myoton AS, Estonia and Myoton Ltd London) is a handheld device that percutaneously applies a mechanical impulse with quick release to the muscle, resulting in muscle oscillations. The oscillations are then measured by an accelerometer and various parameters are calculated simultaneously. The myotonometric measurements obtained using this system have demonstrated good validity [16], optimal relative and absolute reliabilities [17], and high sensitivity to changes [18]. Several studies have shown the feasibility of using this device to monitor the mechanical properties of skeletal muscles in athletes [16].

The unilateral nature of football has been proposed as an important contributing factor to the aetiology of BFIh injury in football players [19]. Previous analyses of the fascicle length and muscle properties of BFIh involved comparisons of right vs left limbs [20] or uninjured vs contralateral injured legs [9, 11], regardless of which limb was dominant. In football the dominant limb is the leg usually used for kicking the ball [21]. Previous research showed that the dominant limb was associated with significant increases in strain magnitude in the BFIh, showing that the muscle strain was greater when kicking with the dominant than with the non-dominant limb [21]. The normal limb dominance characteristics were found to be affected in the presence of a previous BFIh injury [22]. On this basis, it is desirable to perform an analysis based on the dominance of the lower limb rather than its location (i.e. right vs. left limb).

Consequently, the purpose of this study was to compare the fascicle length, pennation angle and mechanical properties of the BFIh of injured vs uninjured legs in injured elite professional football players, and dominant vs non-dominant limbs in uninjured elite professional football players. It was hypothesized that fascicle length is shorter in the previously injured leg in comparison with the uninjured leg in elite professional football players. The properties of the BFIh can discriminate between the common tendon, distal and proximal regions, and between previously injured and uninjured legs in elite professional football players.

MATERIALS AND METHODS

Participants

Fifteen international-level elite professional football players were recruited to participate in this study (mean $\pm$ SD; age: 23.9 ± 3.6 years, height: 1.83 ± 0.09 m, and weight: 77 ± 10.4 kg). Eight players had no previous hamstring injuries and seven players had suffered a hamstring injury during the previous three seasons. Injured players obtained a diagnosis of functional disorder (14%), muscle strain injury I (43%) and muscle strain injury II (43%), and they returned to full activity following mild (4–7 days, 14%), moderate (8–28 days,

57%) and severe (> 28 days, 29%) injury [23]. The diagnosis of prior hamstring strain injury was made with MRI, ultrasound or a combination of both in most cases, in addition to the clinical assessment by the club doctor. The study was conducted according to the Declaration of Helsinki, and the protocol was fully approved by the ethics and research committee of the Virgen Macarena and Virgen del Rocío university hospitals (0398-N-17) before recruitment. After a detailed explanation of the aims, benefits, and risks involved in this investigation, all participants gave written informed consent.

Procedure

Ultrasound imaging

A specialist in sports ultrasonography, with 10 years of experience, performed a standardized ultrasound evaluation of the BFIh in the study participants, at the medical department of FC Basel (Switzerland). Ultrasound images were acquired with a GE-LogiQ S7 ultrasound device (GE Healthcare, Milan, Italy) using a linear 50 mm transducer with an imaging depth field of 8 cm (ML6-15). Participants were instructed to rest in a prone position with the knees extended and the feet relaxed down the side of the bed for better comfort. They were also asked to remain relaxed during the image acquisition. In order to obtain panoramic images of the whole muscle, the EFOV ultrasound technique was used. An ultrasound identification was carried out over the muscle-tendon junctions (MTJs). While the transducer was oriented transversely to the long axis of the muscle, the probe was gradually moved distally or proximally to locate the distal or proximal MTJ respectively. The transducer was oriented longitudinally at the intersection of the superficial and deep aponeuroses, and a mark was drawn on the skin when the smallest muscle section was examined [24]. Once the MTJs were located, the best ultrasound imaging path for BFIh was marked along the horizontal plane by following its fascicles along the superficial compartment proximo-distally. To acquire the EFOV images, a constant pressure was applied to the transducer as it was moved slowly and continuously along the marked path from the proximal to the distal MTJ. The transducer orientation was continuously adjusted to keep it on the fascicle plane so that the fascicles would appear as a continuous and visible pattern, while the aponeuroses stayed parallel. To improve the acoustic contact and to keep the transducer pressure on the skin to a minimum, transmission gel was used for all scans. The region of interest was set in line with the site within the BFIh belly where both superficial and mid-belly aponeuroses were as parallel as possible, the muscle thickness (i.e. the distance between the superficial and midbelly aponeurosis) was the greatest, and the hyperechoic lines delineating the BFLH fascicles (i.e. perimysial membranes) were visible for the maximum length. Longitudinal and transverse scans were carried out to locate this region of interest. Repeated measures could then always be executed at the same site using a line purposely drawn on the skin surface corresponding to the midpoint of the region of interest and two markers drawn on both sides of the transducer so that it was in line with the midpoint of the sonogram field of view [25].

Biceps femoris long head architecture analysis

An image-processing program (ImageJ 1.52p, National Institutes of Health, Bethesda, USA) was used to digitize fascicle length and pennation angle. With the goal of detecting suitable fascicles for analysis, the fascicle insertion point into the intermediate aponeurosis needed to be clearly evident and a reasonable portion of the fascicle (at least ~25% of the total estimated length) needed to be perceivable within the ultrasound transducer's field of view. Four fascicles in the same region of interest were considered for analysis. Fascicle length was the distance (mm) from the intermediate to the superficial aponeuroses, directly evaluated using the segmented line tool. This tool allowed fascicle and superficial aponeurosis curvature to be calculated. The angle between the drawn fascicle and the intermediate aponeuroses was measured as angle pennation (°) [6]. Fascicle length evaluation and angle pennation by the same assessor showed very high reliability *within the same day* (ICC 95% CI: 0.99 (0.99–1.00); CV (%): 1.0% (0.8–1.5%) and 0.99 (0.98–1.00); CV (%): 2.1% (1.6–3.1%), respectively).

Myotonometry mechanical properties

The participants lay prone on a standard examination bed during measurement of the mechanical properties of BFLh with the MyotonPRO (Myoton AS, Estonia and Myoton Ltd London). Oscillation frequency (F, Hz), logarithmic decrement (D, arbitrary units), dynamic stiffness (S, N/m), mechanical stress relaxation time (R, ms), and creep (C, Deborah number) were measured. Oscillation frequency describes the intrinsic tension of the muscle in the resting state with no voluntary contraction, indicating muscle tone. Dynamic stiffness indicates the resistance to contraction or an external force that deforms the muscle's initial shape. Logarithmic decrement describes muscle elasticity in terms of the recovery of the muscle's initial shape after contraction or removal of an external force. Mechanical stress relaxation time represents the time required for restoration of muscle shape after deformation due to voluntary contraction or removal of

an external force. Creep signifies the gradual elongation of the muscle over time when constant tensile stress is applied. Measurement points, which included the common tendon and the proximal and distal position of each BFLh, were determined by ultrasound imaging as previously described. At each site, the mean value of two sets of five consecutive measurements was used for analysis. If the coefficient of variation was more than 3%, the measurement was repeated. The myotonometric measurements used in this system have shown good validity [16], optimal relative and absolute reliability [17] and high sensitivity to changes [18].

Statistical analyses

Data are presented as mean $\pm$ SD. Before conducting statistical analyses, we tested the data distribution using the Shapiro-Wilk test of normality. We performed a two-way ANOVA to test all the possible interactions between measurement points and limbs, and the fascicle length and properties of BFLh. We also tested the main effects of those factors. Finally, we performed a post-hoc analysis for pairwise comparisons with a Bonferroni adjustment. We set the significance level at $p < 0.05$. For these the analyses, we used JASP statistical software (JASP Team, 2020, v.0.12.0) for Windows. The effect sizes (ES, 95% confidence limit [26]) of the selected variables were calculated using the pooled pre-training SDs. The threshold values for the Cohen ES statistics were > 0.2 (small), > 0.6 (moderate), and > 1.2 (large) [27]. The chance that any difference was better/greater (i.e., greater than the smallest worthwhile change, or SWC [0.2 multiplied by the between-subject standard deviation based on the Cohen's d principle, ES]), similar or worse/smaller than that of the other group was subsequently calculated. The probabilities of beneficial/better or detrimental/poorer effects were qualitatively assessed as follows [27]: $< 1\%$, most likely not; $> 1\text{--}5\%$, very unlikely; $> 5\text{--}25\%$, unlikely; $> 25\text{--}75\%$, possible; $> 75\text{--}95\%$, likely; $> 95\text{--}99\%$, very likely; and $> 99\%$, most likely. If there was a chance that the true value was $> 25\%$ beneficial and $> 0.5\%$

TABLE 1. Descriptive data of myotonometry mechanical properties for different measurement points of biceps femoris long head (BFLH). Data are Mean $\pm$ SD.

	Different measurement points of BFLH			Common Tendon vs. Distal			Proximal vs. Distal		
	Proximal (n = 30)	Common Tendon (n = 30)	Distal (n = 30)	ES (95%CI)	Probabilities	p value	ES(95%CI)	Probabilities	p value
Frequency (Hz)	15.54 $\pm$ 1.75	15.82 $\pm$ 1.75	18.17 $\pm$ 1.5	1.28 $\pm$ 0.38	100 / 0 / 0	< 0.001	1.51 $\pm$ 0.38	100 / 0 / 0	< 0.001
Stiffness (N/m)	276 $\pm$ 49.6	283.5 $\pm$ 46.1	337 $\pm$ 33.9	1.09 $\pm$ 0.36	100 / 0 / 0	< 0.001	1.2 $\pm$ 0.35	100 / 0 / 0	< 0.001
Decrement (au)	1.365 $\pm$ 0.27	1.381 $\pm$ 0.26	1.219 $\pm$ 0.08	0.57 $\pm$ 0.32	0 / 0 / 100	0.035	0.45 $\pm$ 0.33	1 / 0 / 99	0.042
Relaxation (ms)	19.51 $\pm$ 3.04	18.87 $\pm$ 2.63	16.01 $\pm$ 1.51	1.14 $\pm$ 0.37	0 / 0 / 100	< 0.001	1.26 $\pm$ 0.36	0 / 0 / 100	< 0.001
Creep (dn)	1.2 $\pm$ 0.6	1.164 $\pm$ 0.14	1.01 $\pm$ 0.9	1.14 $\pm$ 0.37	0 / 0 / 100	< 0.001	1.28 $\pm$ 0.37	0 / 0 / 100	< 0.001

au: arbitrary units; dn: Deborah number

TABLE 2. Descriptive data for biceps femoris long head (BFLH) myotonometry mechanical properties, angle of pennation and length fascicle, and comparison between limbs of injured players and uninjured players. Data are Mean $\pm$ SD

	Previously Injured Players (IP)		Uninjured Players (UP)		IPI vs. UPD		
	Injured Limb (IPI; n = 7)	Uninjured Limb (IPU; n = 7)	Dominant Limb (UPD; n = 8)	Non-Dominant Limb (UPND; n = 8)	ES(95%CI)	Probabilities	p value
Frequency (Hz)	17.63 $\pm$ 1.68	17.34 $\pm$ 1.85	15.68 $\pm$ 1.81*†	16.15 $\pm$ 2.14*	1.01 $\pm$ 0.51	100 / 0 / 0	0.031
Stiffness (N/m)	331 $\pm$ 37.57	317.2 $\pm$ 42.67	279.5 $\pm$ 48.89*†	288.3 $\pm$ 42.67*	0.95 $\pm$ 0.44	100 / 0 / 0	0.02
Decrement (au)	1.367 $\pm$ 0.222	1.351 $\pm$ 0.213	1.298 $\pm$ 0.234	1.301 $\pm$ 0.247	0.30 $\pm$ 0.53	83 / 0 / 17	1
Relaxation (ms)	16.38 $\pm$ 1.75	17.08 $\pm$ 2.33	19.33 $\pm$ 3.035*†	18.59 $\pm$ 3.007*	0.98 $\pm$ 0.47	0 / 0 / 100	0.017
Creep (dn)	1.032 $\pm$ 0.1	1.066 $\pm$ 0.130	1.194 $\pm$ 0.165*†	1.146 $\pm$ 0.159*	0.98 $\pm$ 0.48	0 / 0 / 100	0.015
Pennation Angle (Degrees)	16.58 $\pm$ 5.66	17.10 $\pm$ 6.56	16.21 $\pm$ 4.67	16.86 $\pm$ 5.37	0.06 $\pm$ 0.82	55 / 0 / 45	1
Length Fascicle (mm)	8.49 $\pm$ 0.94	8.56 $\pm$ 0.95	9.356 $\pm$ 1.257	9.311 $\pm$ 1.295	0.64 $\pm$ 0.77	8 / 0 / 92	0.933

* Significant differences with IPI; † Significant differences with IPU; au: arbitrary units; dn: Deborah number

harmful, then the clinical effect was considered to be unclear [27]. However, the clinical inference was declared to be beneficial when the odds ratio of benefit/harm was > 66 [27].

RESULTS

Descriptive data for BFLH mechanical properties in different measurement regions, fascicle length and pennation angle in injured players (IP: injured limb (IPI) and uninjured limb (IPU)) and uninjured players (IU: dominant limb (UPD) and non-dominant limb (UPND)) are shown in Tables 1 and 2 respectively. No significant time $\times$ group interaction was observed between variables. A significant effect was observed between different myometric regions of BFLH measured and frequency ($\eta^2_p = 0.306$; $p < 0.001$), stiffness ($\eta^2_p = 0.245$; $p < 0.001$), decrement ($\eta^2_p = 0.108$; $p = 0.021$), relaxation ($\eta^2_p = 0.162$; $p < 0.001$), and creep ($\eta^2_p = 0.220$; $p < 0.001$). The elite professional football players showed significantly higher distal BFLH frequency, stiffness, decrement, relaxation, and creep than in the common tendon and proximal regions (see Table 1). A significant effect was observed between the injured players' limbs (i.e. IPI and IPU), the uninjured players' limbs (i.e. UPD and UPND) and frequency ($\eta^2_p = 0.160$; $p < 0.001$), stiffness ($\eta^2_p = 0.145$; $p < 0.001$), relaxation ($\eta^2_p = 0.140$; $p < 0.001$), and creep ($\eta^2_p = 0.140$; $p < 0.001$). The IPI and IPU showed significantly higher frequency ($p = 0.004$ and $p = 0.05$ respectively) and stiffness ($p = 0.004$ and $p = 0.005$ respectively) and significantly lower relaxation ($p = 0.003$ and $p = 0.044$ respectively) and creep ($p = 0.002$ and $p = 0.05$ respectively) than UPD. The IPI showed significantly higher frequency ($p = 0.005$) and stiffness ($p = 0.002$) and significantly lower relaxation ($p = 0.013$) and creep ($p = 0.008$) than UPND (see Table 2). There were no differences between IPI and IPU, or between UPD and UPND.

DISCUSSION

The purpose of this study was to compare the fascicle length, pennation angle and mechanical properties of the BFLH of injured vs. uninjured legs in injured elite football players, and dominant vs. non-dominant limbs in uninjured elite football players. The main findings of this study were: a) the properties of the BFLH were different in the distal region in comparison with the proximal region and common tendon; b) frequency, stiffness, relaxation, and creep properties of BFLH were different in previously injured players vs. uninjured players; and c) there were no differences among injured players in fascicle length and pennation angle of BFLH between previously injured and uninjured legs, or between the dominant and non-dominant limbs in uninjured players.

The present study is the first to explore the mechanical properties of the BFLH using myotonometric measurements in elite professional football players. In football, winning ball possession, passing a defending player or gaining a position to score a goal are determined by the player's ability to accelerate [28]. This acceleration is strongly determined by the horizontal ground reaction force and therefore by the football player's ability to activate their hamstring muscles just before ground contact, which has the greatest capacity to produce eccentric knee flexor peak torque [29]. It has been reported that football players returning to play after rehabilitation from a hamstring injury can display a decrease in horizontal force production [30]. Although some research showed that injured athletes may experience apprehension about experiencing pain when producing a high level of force [31], our results agree with these findings since the IPI and IPU BFLH in elite professional football players may have less potential to produce eccentric peak torque, as extrapolated from myotometer data (i.e. higher F and S, and lower C) [18]. From our experimental design, we could not determine whether the decrease in horizontal force production was linked to knee flexion or hip extension

of the BFIh. However, our results indicated that in elite professional football players, the distal region of the BFIh showed a poor capacity to produce eccentric force (i.e. higher F and S, and lower C) compared to the common tendon area or proximal region of the BFIh (see Table 1). Based on the knowledge that a more compliant musculotendinous system has a greater capacity to elongate, enabling external forces to be absorbed over a greater distance and time, thereby creating a cushioning effect [32], our myotonometric values showed higher intrinsic tension in the muscle in the resting state (i.e. F), higher resistance to external force that deforms the muscle's initial shape (i.e. S) and a significant decline in the ability to provide a gradual elongation of the muscle over time when constant tensile stress is applied (i.e. C), in IPI compared to UPD and UPND and IPU compared to UPD. There are no myotonometric values of BFIh for this cohort (elite professional football players); therefore we cannot compare our data with other studies in professional football. However, our results are in line with a prospective study with elite netball players that found higher stiffness (i.e. F) in the soleus and Achilles tendon of injured compared with uninjured athletes [33]. In our case, there were no differences between injured and uninjured limbs in the injured players, or between dominant and non-dominant limbs in the uninjured players. While it is evident that passive muscle stiffness measured using myotonometry is sensitive to changes induced by eccentric exercises [34], further research is needed to track BFIh injuries in football players over time, and to analyse whether the stiffness is a contributing factor in return to play.

It is known that football training and competition induce greater increases in concentric than eccentric strength in the BFIh [35], favouring shortening of the fascicles of this musculature [36, 37]. The fascicle lengths of elite professional football players in our study (~9 cm) were slightly longer than those observed in under-19 football players (8.5 cm) [8], although shorter than those observed in Australian professional football players (10.63 cm.) [9], senior football players (10.12 cm) [20] and young professional football players (10.55 cm) [4], before subjecting them to specific training programmes to increase the fascicle length. The younger age of the football players in the study by Lacombe et al. [8] could also explain the slight differences in comparison with our results (both studies used EFOV), as muscles and fascicles generally tend to lengthen with growth [38]. Comparison with the other studies would not be appropriate because, as Franchi et al. [6] showed, the linear extrapolation of visible fascicles from a single ultrasound image results in an overestimation of BFIh when compared with EFOV scans, which could explain the differences between studies.

Previous research suggests that professional football players with shorter fascicles (fewer in-series sarcomeres) may be more susceptible to overstretching and damage caused by powerful eccentric contractions, such as those performed during the terminal swing

phase of high-speed running [9]. In addition, Timmins et al. [12] observed that previously injured limbs had shorter BFIh fascicles than the contralateral uninjured limbs and the two-limb-average of the uninjured players when assessed at rest. In contrast to this and using EFOV ultrasound scans, our results with elite professional football players showed that there were no differences in fascicle length between the previously injured limb in comparison with the uninjured limb. The method by which the return to play process after injury is performed will have a substantial impact on the subsequent state of the BFIh muscle tissue. Despite the nonuniform nature of BFIh architecture [39], a possible explanation for this fact could be that the elite football players analysed in our study were fully recovered from their hamstring injury with no repercussions or sequelae, and were training and competing weekly in elite professional football.

This study has some limitations associated with the ultrasound methodology to infer muscle fascicle lengths [20, 25, 40]. However, the method used in this study, manual linear extrapolation, has recently been recommended due to its lower fascicle estimation and greater accuracy in comparison with the trigonometric equation methods used in other studies [6].

CONCLUSIONS

We describe, for the first time, reference values for BFIh fascicle length with EFOV scans, pennation angle and myotonometric values in previously injured vs uninjured limbs and in dominant vs non-dominant legs in elite professional football players. The properties of the BFIh were different in the distal region in comparison with the proximal region and the common tendon area. The previously injured limb showed higher intrinsic tension in the muscle in the resting state, higher resistance to external force that deforms the muscle's initial shape, and a significantly reduced ability to provide a gradual elongation of the muscle over time when constant tensile stress was applied, but a similar muscle architecture. The BFIh fascicle lengths and pennation angle in elite professional football players showed no differences in previously BFIh injured vs uninjured legs or in dominant vs non-dominant limbs in uninjured players.

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Conflict of interest

The authors declared no conflict of interest.

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The effects of normobaric hypoxia on the leukocyte responses to resistance exercise

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ABSTRACT: There is growing interest in the use of systemic hypoxia to improve the training adaptations to resistance exercise. Hypoxia is a well-known stimulator of the immune system, yet the leukocyte responses to this training modality remain uncharacterised. The current study characterised the acute leukocyte responses to resistance exercise in normobaric hypoxia. The single-blinded, randomised trial recruited 13 healthy males aged 18–35 years to perform a bout of resistance exercise in normobaric hypoxia (14.4% O₂; n = 7) or normoxia (20.9% O₂; n = 6). Participants completed 4 × 10 repetitions of lower and upper body exercises at 70% 1-repetition maximum. Oxygen saturation, rating of perceived exertion and heart rate were measured during the session. Venous blood was sampled before and up to 24 hours post-exercise to quantify blood lactate, glucose and leukocytes including neutrophils, lymphocytes, monocytes, eosinophils and basophils. Neutrophils were higher at 120 and 180 minutes post-exercise in hypoxia compared to normoxia (p < 0.01), however lymphocytes, monocytes, eosinophils and basophils were unaffected by hypoxia. Oxygen saturation was significantly lower during the four exercises in hypoxia compared to normoxia (p < 0.001). However, there were no differences in blood lactate, heart rate, perceived exertion or blood glucose between groups. Hypoxia amplified neutrophils following resistance exercise, though all other leukocyte subsets were unaffected. Therefore, hypoxia does not appear to detrimentally affect the lymphocyte, monocyte, eosinophil or basophil responses to exercise.

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INTRODUCTION

Resistance exercise causes a profound change in the number of leukocytes in the systemic circulation that can persist for hours after the exercise bout. Although endurance exercise has featured in much of the exercise immunology literature, interest is growing in how the five leukocyte populations respond to different resistance training protocols; neutrophils, lymphocytes, monocytes, eosinophils and basophils [1].

An acute bout of moderate- to high-intensity resistance exercise increases the number of circulating neutrophils that typically peak between 90 and 120 minutes post-exercise [2, 3]. Similarly, monocyte concentrations increase immediately following a bout of resistance exercise and remain elevated for up to 120 minutes [2, 3]. In addition to their role in innate immunity, these phagocytic populations are important mediators of skeletal muscle repair and adaptation [4]. The mechanical strain associated with resistance exercise induces myofiber damage, which results in the release of inflammatory cytokines from skeletal muscle [5]. These inflammatory cytokines and

other chemotactic factors attract neutrophils and macrophages to skeletal muscle [6], where they play a vital role in the degradation of damaged muscle and the subsequent adaptation of skeletal muscle tissue [4].

Lymphocytes are typically elevated 2-fold immediately following an acute bout of high-intensity resistance exercise, termed lymphocytosis [7]. Lymphocytopenia then occurs, where lymphocyte concentrations drop below resting levels approximately two hours post-exercise [7]. The subsequent lymphocytopenia in the hours following resistance exercise could be partly caused by the sequestering of lymphocytes back into tissues such as the lungs and lymphoid tissues, in addition to any damaged muscle tissue [8]. Although lymphocyte subsets such as T lymphocytes likely contribute to skeletal muscle regeneration [9], much of the exercise immunology literature focuses on their role in resistance to infection [10]. The mechanisms modulating the immune cell responses to exercise are not fully understood, though they likely include

an increase in circulating adrenaline during exercise that stimulates β -2-adrenergic receptors on neutrophils [11], lymphocytes [12] and macrophages [13, 14]. The sympathetic stimulation of adrenaline increases almost linearly with exercise intensity and therefore the leukocyte response is likely intensity dependent [14, 15]. Whilst the leukocyte responses to training variables such as nutrient status [16] and inter-set rest periods [2] are well characterised, there are many novel resistance training strategies that have not been investigated. There is growing interest in the use of systemic hypoxia to improve the training adaptations to resistance exercise [17], yet little is known about the collective effects of resistance exercise and systemic hypoxia on circulating leukocyte populations.

Performing resistance exercise at simulated altitude is a novel strategy to enhance muscle hypertrophy and strength gains to a greater extent than the equivalent training in normoxia [17, 18]. Many recreational training facilities now offer simulated altitude training rooms where the air pressure is equivalent to sea level, but the environmental O_2 is reduced to 12–16%, equating to approximately 1,800–4,000 m above sea level (termed normobaric hypoxia) [19]. Although most hypoxic training studies focused on the muscle hypertrophy and strength adaptations, systemic hypoxia is a potent regulator of circulating leukocyte populations. Acute exposure to hypoxia for twenty minutes can modulate the number of circulating leukocytes such as lymphocytes (natural killer cells) and monocytes in healthy individuals [20]. Pedersen *et al.* [21] suggested that acute exercise and hypoxia exposure are additive stimuli to the immune system, where greater immunological stress is induced by performing exercise in hypoxia. A contributor to this response may be an increase in relative exercise intensity, where there is increased reliance on anaerobic metabolism and increased sympathetic activity in hypoxia [22, 23]. However, Katayama *et al.* [24] showed that performing dynamic leg exercise in hypoxia (12.7% O_2) elicits greater muscle sympathetic nerve activity than normoxia even when controlling for relative exercise intensity. Systemic hypoxia also activates other pathways including hypoxia-inducible factor 1 (HIF-1) and Nuclear Factor kappa-light-chain-enhancer of activated B cells (NF- κ B) which are both well-known to stimulate leukocyte populations [25, 26].

Acute resistance exercise alone can mobilise leukocytes into the circulation through increased circulating adrenaline, noradrenaline and growth hormone [27]. Hypoxia can amplify the acute hormonal responses to resistance exercise in young adults [28, 29] and thus hypoxia may also amplify the leukocyte responses to resistance exercise. Currently, there are no studies investigating the leukocyte responses of healthy adults to moderate-intensity resistance exercise in hypoxia.

Therefore, this study characterised the acute leukocyte responses of healthy adults to a single bout of resistance exercise in either normobaric hypoxia or normoxia. We hypothesised that hypoxia would amplify the acute leukocyte responses to resistance exercise.

MATERIALS AND METHODS

Experimental design

The study was designed to investigate the acute effects of hypoxic resistance exercise on the dependant variable; leukocytes. The study was performed in accordance with the ethical standards of the Helsinki Declaration and was approved by the Deakin University Human Research Ethics committee (reference number: 2016-308). After the nature and risks of the research were explained to the participants, written informed consent was obtained from participants.

Statistical power for the study was calculated using a priori in G*Power through repeated measures analysis of variance (ANOVA), within-between factors (the F test; Version 3.1.9.4; Universität Kiel, Germany). The power analysis was designed to examine the additive effect of hypoxia on the leukocyte response to resistance exercise. Therefore we identified a study that examined an additive stimulus (vitamin supplementation) on the leukocyte responses to resistance exercise [30]. Neutrophils were selected as the largest leukocyte subpopulation in systemic circulation and 120 minutes post-exercise was selected as the most meaningful time point. Cohens *d* was first calculated and then transformed into effect size *f*. The following parameters were used; Alpha error probability (0.05), power (1- β error probability; 0.80), groups (two), number of measurements (two; pre-exercise and 2 hours post-exercise), standard correlation among repeated measures (0.5), non-sphericity correction (one). Therefore, to detect an effect size (*f*) of 0.620 using a two-way repeated measures ANOVA for mean neutrophil count, a minimum of four participants in each group were required for this study. Thirteen participants were recruited to account for potential dropout and variation in leukocyte responses.

Subjects

The single-blinded randomised study recruited 13 apparently healthy adult males aged 18–35 years. Participants were randomly allocated to complete a single bout of resistance exercise in normoxia at 20.93% O_2 ($n = 6$) or hypoxia at 14.4% O_2 ($n = 7$). Normobaric

Table 1. Participant characteristics. Data is presented as mean $\pm$ SD.

	Hypoxia ($n = 7$)	Normoxia ($n = 6$)
Age (years)	22.1 $\pm$ 2.5	23.7 $\pm$ 2.6
Height (m)	1.81 $\pm$ 0.08	1.83 $\pm$ 0.03
Weight (kg)	75.9 $\pm$ 9.6	77.6 $\pm$ 9.5
BMI ($[kg/m^2]$)	23.3 $\pm$ 2.5	23.3 $\pm$ 3.2
$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	49.4 $\pm$ 2.96	47.7 $\pm$ 1.69

M, metres; kg, kilograms; BMI, body mass index.

hypoxia was achieved in an environmental chamber using a normobaric hypoxic generator (Pulford Systems, Australia). Ambient air was enriched with N₂ to reduce the O₂ in the environmental chamber to 14.4% O₂, equivalent to an altitude of approximately 3,300 m above sea level [19]. Participants were non-smokers, non-diabetic and recreationally active. Participants had not partaken in a heavy resistance training program for a minimum of six months prior to the study and had no prolonged exposure to altitude above 3000 m within the previous six months.

Procedures

Participants attended Deakin University Waurn Ponds for anthropometric measurements and a familiarisation to the exercise testing protocols. After at least three days' rest, participants returned for physical fitness testing in normoxia at approximately 7.30 am in a fasted and rested state. Participants were asked to abstain from alcohol, caffeine and exercise in the 24 hours before the testing. Cardiovascular fitness was assessed with a maximal incremental test on a stationary cycle ergometer (Excalibur sport bicycle ergometer, Lode, Netherlands) using a step protocol previously reported in young adults [31]. Participants were fitted with a heart rate strap (Polar T34, Polar Electro Oy, Finland) and facemask for the duration of the test. The protocol comprised a two-minute warm-up at 50 Watts, after which the load was increased by 25 Watts every 60 seconds until volitional exhaustion. Oxygen consumption ($\dot{V}O_2$) was measured continuously throughout the test for the determination of $\dot{V}O_{2max}$. The test was terminated when participants cycled below 60 revolutions per minute for 5 seconds, or the American College of Sports Medicine (ACSM) exercise termination criteria were met. $\dot{V}O_{2max}$ was verified by a stable $\dot{V}O_2$ despite an increased workload, a heart rate within 10% of the predicted maximum and a respiratory exchange ratio > 1.1.

Muscular strength was determined with a five repetition maximum (5RM) test of lower body (squat and split squat) and upper body (pectoral-fly and upright row) exercises using a standardised protocol according to the ACSM [32]. The upper and lower body exercises were chosen to activate multiple large muscle groups. Furthermore, a 5-RM assessment was selected for safety reasons and the untrained state of participants. From the 5-RM results, estimated 1-RM was calculated using the formula below [33]:

Upper body calculation: 1-RM = 1.1307 (5-RM) + 0.6998.

Lower body calculation: 1-RM = 1.09703 (5-RM) + 14.2546.

Training Session

On the day of testing, participants reported to Deakin University at approximately 7.30 am after an overnight fast. Resting measurements of heart rate and oxygen saturation (SpO₂; Prince 100F handheld pulse-oximeter with finger attachment, Healforce, China) were taken and a venous blood sample (10 mL) was collected from an antecubital vein. Participants then entered the environmental chamber for a 10-minute acclimation, followed by a five-minute low-intensity

warm up on a cycle ergometer. The resistance exercise session consisted of four sets and ten repetitions of four exercises (in the following order); split squat, pectoral fly, standing row and squat. The exercises were conducted at 70% of the participants calculated 1-RM with a one-minute rest between sets and a two-minute rest between exercises. Upon completion of the final set, a 22-gauge intra-vascular catheter (Smiths Medical International) was inserted into an antecubital vein. Venous blood was collected immediately post-exercise and at 15, 30, 60, 120 and 180 minutes post-exercise. Blood was collected with a syringe at each time point and carefully transferred to the vacutainer to reduce the risk of haemolysis in the blood samples. Participants were provided a standardised meal for dinner that comprised of approximately 65% carbohydrates, 20% fat and 15% protein. Participants returned the following morning rested and fasted for a 24-hour blood sample.

SpO₂ and heart rate were measured after the 10-minute acclimation to the environmental condition and immediately after each resistance exercise set was completed. Rating of perceived exertion (RPE) was assessed using the Borg Category Ratio 10 scale. Responses ranged from no exertion to maximal exertion on a 0–10 scale. Blood glucose and lactate were measured at each time point using an Accu-chek Performa Nano device (Roche Diabetes Care, Mannheim, Germany) and lactate pro 2 device (Arkay Factory Inc., Shiga, Japan), respectively.

A full blood count was performed on the EDTA-treated whole blood samples using a haematology analyser (DhX500, Beckman Coulter, Australia) to quantify total leukocyte, neutrophil, lymphocyte, monocyte, eosinophil and basophil concentration. The full blood count also quantified red blood cells, haemoglobin and platelets. Samples were run on the same day as blood collection. The haematology analyser was regularly cleaned and a 3-point calibration was performed before testing each sample batch. Due to the plasma volume shifts that occur with exercise, these were calculated and accounted for using the Dill and Costill formula [34].

Statistical analysis

Data were graphed using GraphPad Prism (version 8.0.0) and tested for normality using the D'Agostino & Pearson test. Basophils did not pass the normality test and therefore underwent Log₁₀ transformation prior to analysis. An independent samples T-test was used to check for differences between normoxia and hypoxia at baseline.

We used a restricted maximum likelihood linear mixed-effects model with fixed effects of group and time (and their interaction) and random intercepts for individuals (allowing for correlated measures across time points) using SPSS (IBM SPSS Statistics 26). This model was used to examine the interaction between group (normoxia, hypoxia) and time (Pre, post 0, 15, 30, 60, 120, 180 minutes and 24 hours). For the SpO₂, heart rate and RPE values, there were six levels of time (Rest, acclimated rest, split squat, pectoral fly, standing row, squat). If a significant interaction was present ($p < 0.05$),

pairwise comparisons were used to identify significant differences between groups at each time point.

RESULTS

There were no significant differences in baseline characteristics between the experimental groups (independent samples T-test; $p > 0.05$).

There was a significant time $\times$ group interaction for SpO_2 ($F[5,35.0] = 5.19$, $p = 0.001$; Figure 1a). Pairwise comparisons showed that SpO_2 was significantly lower in the hypoxic group following the 10-minute acclimation (estimated mean difference = -4.65 [95% CI: $-2.11, 3.61$], $p = 0.002$), the split squat (estimated mean difference = -8.35 [95% CI: $-11.21, -5.49$], $p < 0.001$), pectoral fly (estimated mean difference = -5.30 [95% CI: $-8.16, -2.44$], $p = 0.001$), standing row (estimated mean difference = -7.85 [95% CI: $-10.71, -4.99$], $p < 0.001$) and squat exercise (estimated mean difference = -6.40 [95% CI: $-9.26, -3.54$], $p < 0.001$), compared to the normoxic group. There was no significant time $\times$ group interaction for heart rate ($F[5,51.0] = 0.96$, $p = 0.453$; Figure 1b), though there was a significant effect of time ($F[5,51.0] = 103.59$, $p < 0.001$), with heart rate peaking after the final squat exercise in both groups. RPE did not show a significant time $\times$ group interaction ($F[3,33.0] = 0.82$, $p = 0.494$), though there was a significant effect of time ($F[3,33.0] = 5.83$, $p = 0.003$; Figure 1c).

Plasma volume shift was accounted for in all blood analysis due to the known plasma shifts that occur with intense exercise between the systemic circulation and the extracellular space (Figure 2). The change in plasma volume was not different between hypoxic and normoxic groups ($F[7,61.1] = 0.94$, $p = 0.482$), though there was a significant effect of time ($F[7,61.1] = 19.2$, $p < 0.001$) where there was a decrease in plasma volume immediately post-exercise that returned close to baseline by 15 minutes.

There was no significant time $\times$ group interaction for blood lactate ($F[7,75.1] = 1.80$, $p = 0.100$; Figure 3a). There was however a significant effect of time ($F[7,61.1] = 88.56$, $p < 0.001$), where both the normoxic and hypoxic groups showed a significant increase in blood lactate above the control group at 0, 15 and 30 minutes post-exercise. Blood glucose was not significantly different between groups ($F[7,75.0] = 1.10$, $p = 0.370$; Figure 3b), though there was a significant effect of time ($F[7,75.1] = 3.30$, $p = 0.004$).

There was a significant time $\times$ group interaction for total leukocyte concentration in the 24 hours following the acute resistance exercise bout ($F[7,75.1] = 4.43$, $p < 0.001$; Figure 4a). Pairwise comparisons showed that total leukocyte concentration was significantly higher in hypoxia at 120 (estimated mean difference = 3.28 [95% CI: $0.67, 5.90$], $p = 0.016$) and 180 minutes (estimated mean difference = 3.89 [95% CI: $1.25, 6.51$], $p = 0.006$) post-exercise compared to normoxia. Platelets showed no significant time $\times$ group interaction ($F[7,74.1] = 0.77$, $p = 0.615$), though there was a significant effect of time ($F[7,75.1] = 5.80$, $p < 0.001$; Figure 4b).

There was a significant time $\times$ group interaction for neutrophil concentration in the 24 hours following the acute resistance exercise bout ($F[7,75.1] = 5.22$, $p < 0.001$; Figure 5a). Pairwise comparisons showed that neutrophils were significantly higher in hypoxia at 120 (estimated mean difference = 3.24 [95% CI: $1.04, 5.43$], $p = 0.006$) and 180 minutes (estimated mean difference = 3.90 [95% CI: $1.67, 6.13$], $p = 0.001$) post-exercise compared to normoxia.

Lymphocyte concentrations did not show a significant time $\times$ group interaction ($F[7,75.1] = 0.98$, $p = 0.456$; Figure 5b). However, there was a significant effect of time on lymphocyte numbers ($F[7,75.1] = 25.12$, $p < 0.001$). There was no significant time $\times$ group interaction present for monocytes ($F[7,75.1] = 1.38$, $p = 0.227$; Figure 5c), though there was a significant time effect ($F[7,75.1] = 8.88$, $p < 0.001$). There was no significant group $\times$ time interactions for basophils ($F[7,80.0] = 0.57$, $p = 0.780$) or eosinophils ($F[7,75.0] = 1.02$, $p = 0.424$), though eosinophils showed a significant effect of time ($F[7,75.0] = 13.0$, $p < 0.001$; Figure 5d, e). The neutrophil to lymphocyte ratio showed a significant time $\times$ group interaction ($F[7,75.1] = 4.86$, $p < 0.001$; Figure 5f). Pairwise comparisons showed that the ratio was significantly higher in hypoxia at 120 (estimated mean difference = 2.50 [95% CI: $0.96, 4.04$], $p = 0.002$) and 180 minutes (estimated mean difference = 2.70 [95% CI: $1.12, 4.27$], $p = 0.001$) post-exercise compared to normoxia.

DISCUSSION

This study characterised the acute leukocyte responses of healthy adults to a single bout of resistance exercise in normobaric hypoxia. We hypothesised that hypoxia would amplify the leukocyte responses to acute resistance exercise.

For the first time, we showed that performing resistance exercise in normobaric hypoxia significantly increases neutrophil concentrations at 120 minutes and 180 minutes post-exercise compared to normoxia. Although the underlying cause of the neutrocytosis is unknown, changes in growth hormone are of great interest in the hypoxic training literature. Exposure to hypoxia during an acute bout of resistance exercise increases the growth hormone response up to 60 minutes post-exercise [28, 29]. Intravenous injection of 2IU recombinant human growth hormone can induce a significant neutrocytosis after 120 minutes [35]. Leukocyte subpopulations including neutrophils possess growth hormone receptors [36] and type 1 IGF-1 receptors [37]. Therefore, it is plausible that the amplified growth hormone response to resistance exercise observed in previous hypoxic studies [28, 29] is linked to the neutrocytosis observed in the current study. However, this is speculative and further research is needed to confirm this potential relationship. Currently the functional consequences of the neutrocytosis are unclear, though it could help to respond to invading pathogens in the circulation [38] and support the repair of skeletal muscle following damaging resistance exercise [39]. Further research is needed to examine the functional capacity of neutrophils following resistance exercise in hypoxia. The

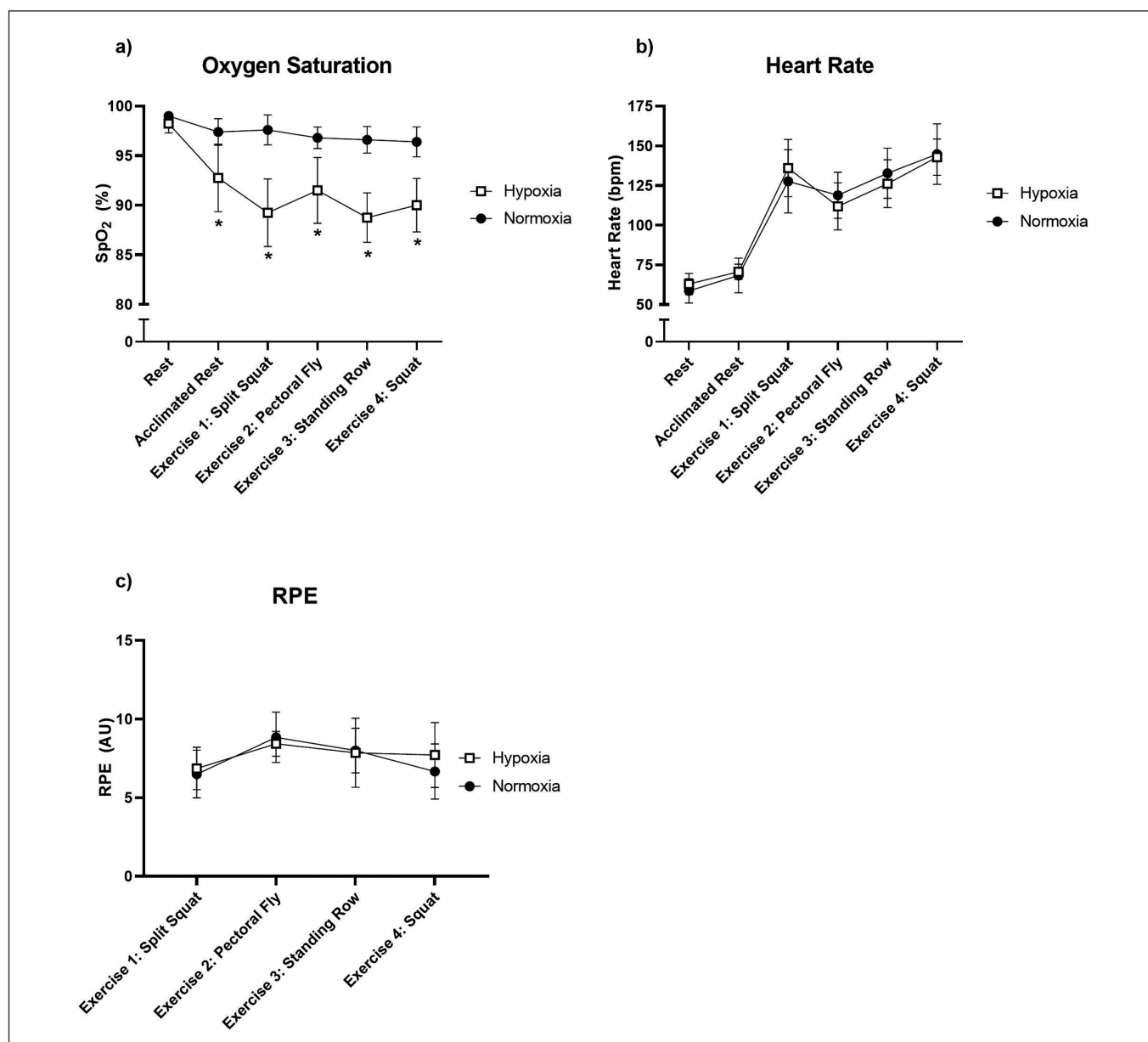


FIG. 1. Oxygen saturation (a), heart rate (b) and rating of perceived exertion (RPE; c) responses to an acute bout of resistance exercise in normoxia or hypoxia. Mean $\pm$ SD. * Significant difference between hypoxia and normoxia ($p < 0.05$).

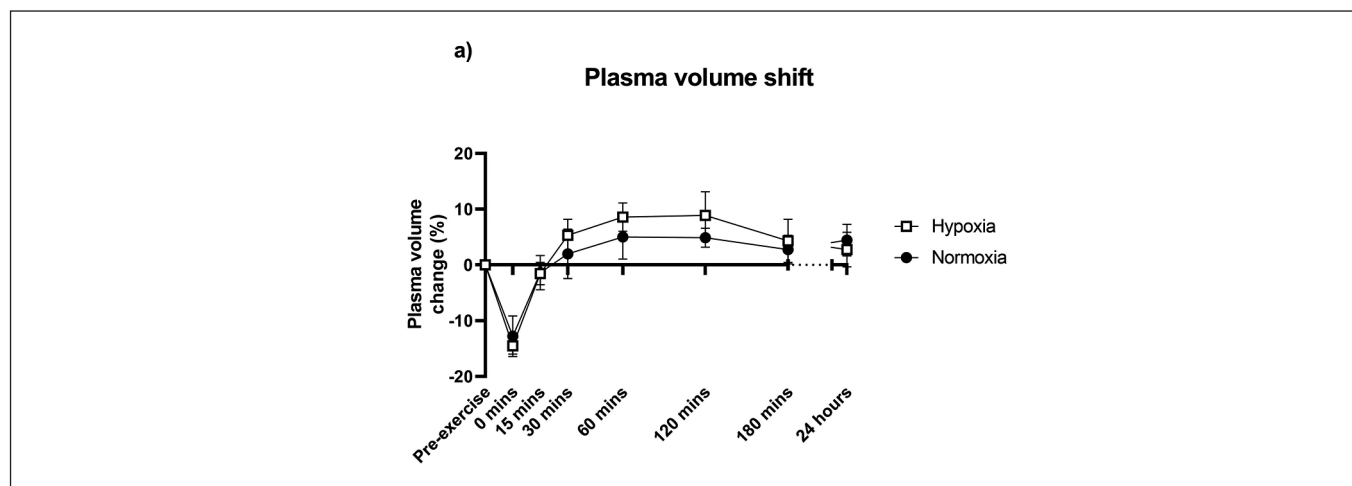


FIG. 2. Plasma volume responses to an acute bout of resistance exercise in normoxia or hypoxia. Mean $\pm$ SD.

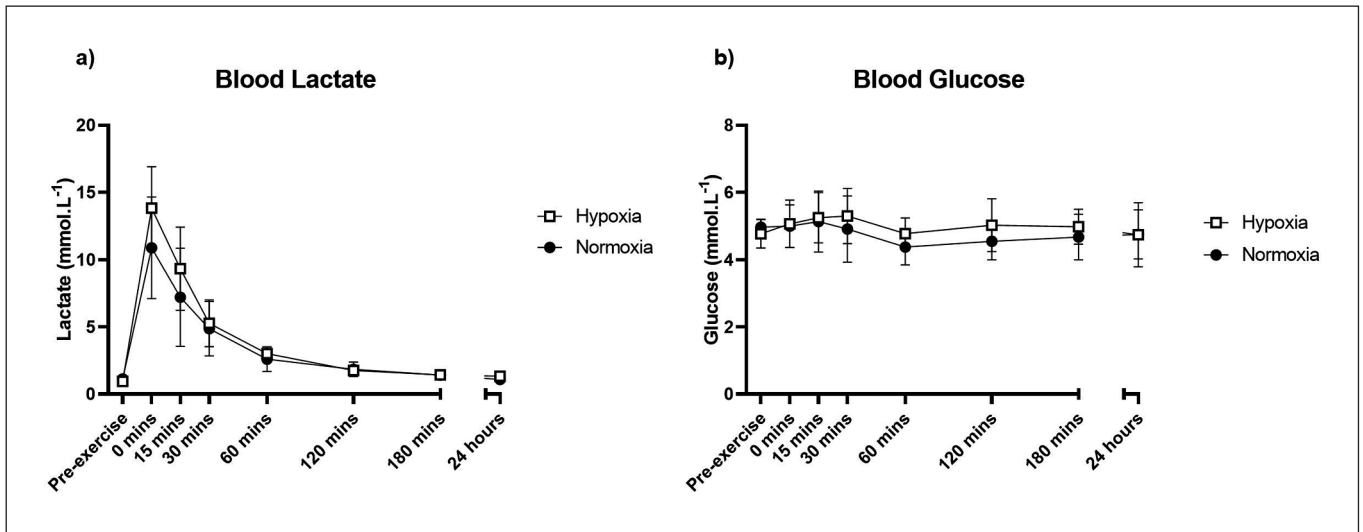


FIG. 3. Blood lactate (a) and blood glucose (b) responses to an acute bout of resistance exercise in normoxia or hypoxia. Mean $\pm$ SD.

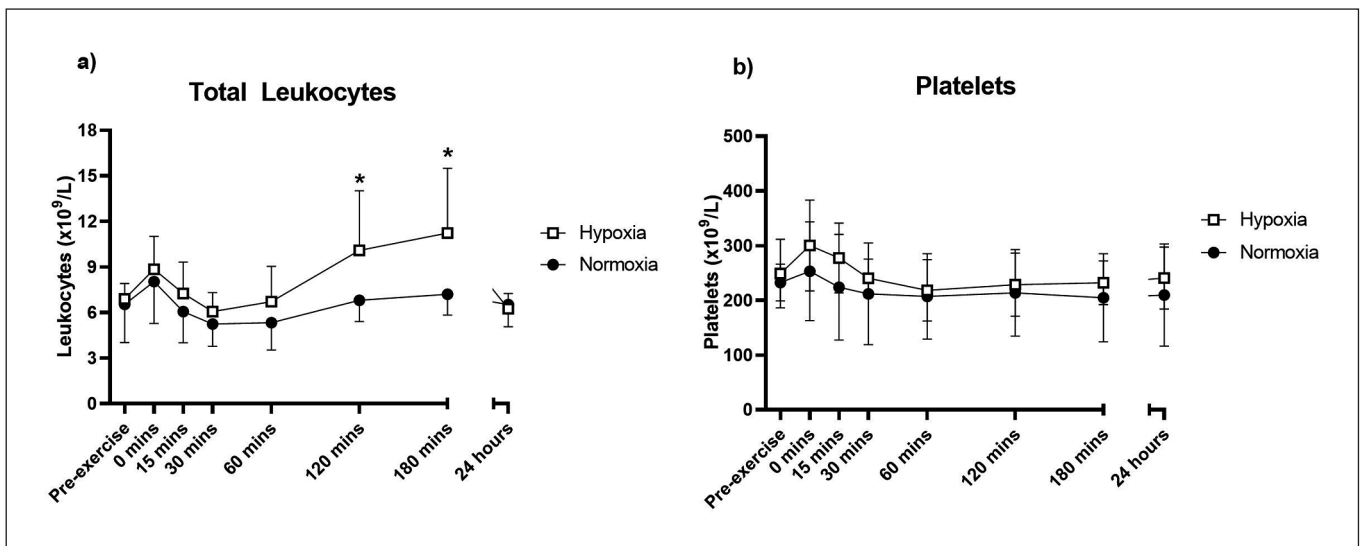


FIG. 4. Total leukocyte (a) and platelet (b) responses to an acute bout of resistance exercise in normoxia or hypoxia. Mean $\pm$ SD. * Significant difference between hypoxia and normoxia ($p < 0.05$).

neutrophil to lymphocyte ratio was also elevated in the hypoxic group at 120 and 180 minutes post-exercise, though it is currently unclear if there are any functional benefits or consequences from an acute increase in this ratio. The neutrophil to lymphocyte ratio is typically measured at rest as prognostic biomarker for conditions such as cancer [40] and sepsis [41].

Surprisingly, there was no effect of hypoxia on circulating lymphocytes in the 24 hours following resistance exercise. Both the normoxic and hypoxic trained groups showed the classic bi-phasic response [42], where a significant increase in lymphocytes at 0 minutes post-exercise was followed by suppression below baseline (lymphocytopenia) for up to three hours. The exercise immunology field is

still divided on whether exercise-induced lymphocytopenia increases the risk of infection and illness as there is little causal data available [43]. Importantly, these findings suggest that performing moderate-intensity resistance exercise under hypoxic conditions does not alter post-exercise immunity. Further studies are needed to determine if leukocyte function changes in response to resistance training in hypoxia. In particular, chronic training programs in hypoxia with larger sample sizes may be able to detect more subtle and long-term leukocyte responses to hypoxic resistance training.

SpO₂ levels were significantly but safely reduced during the resistance training bout in hypoxia, with the SpO₂ in the hypoxic group dropping to a minimum of $91.8 \pm 4.7\%$ following the split squat

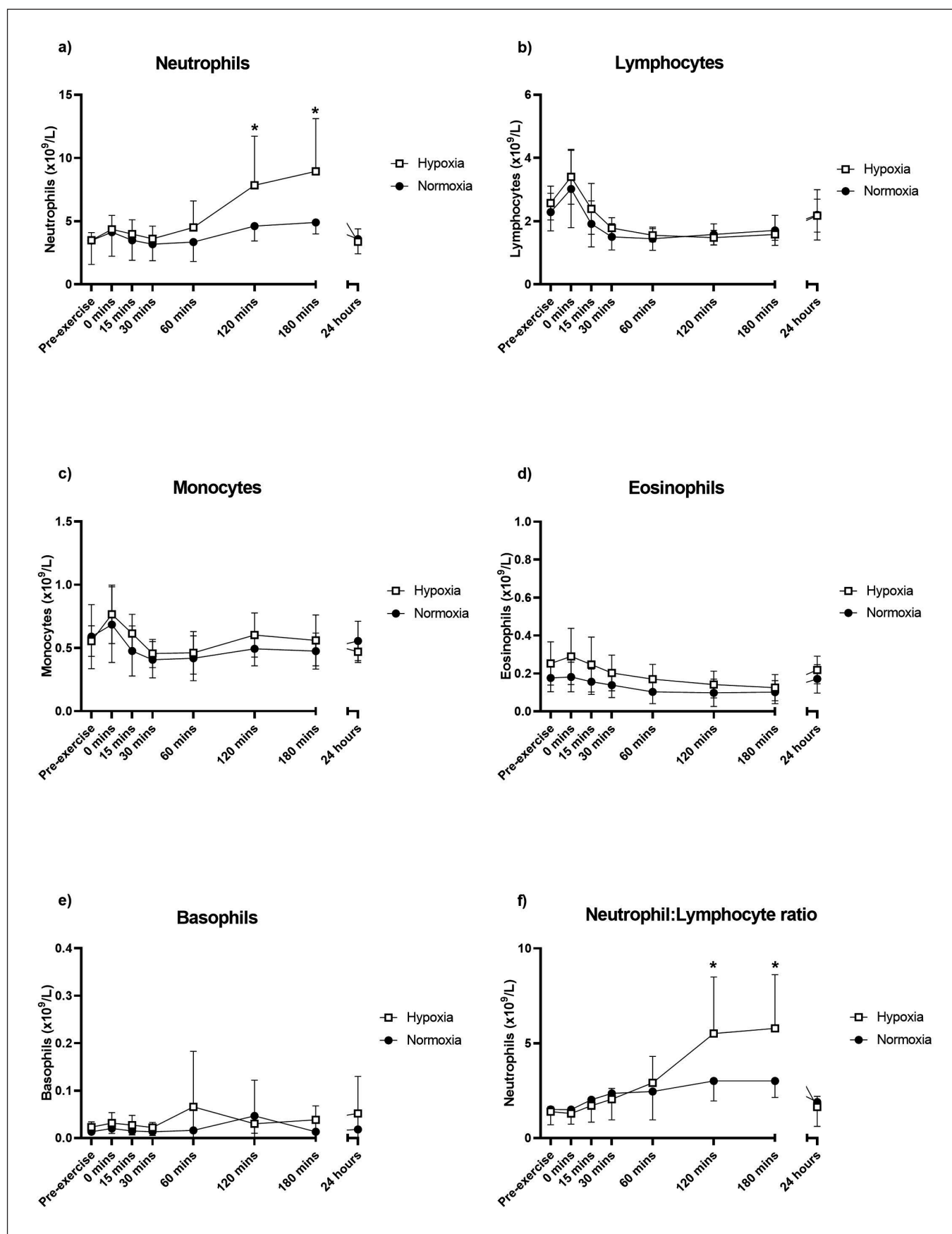


FIG. 5. Neutrophil (a), lymphocyte (b), monocyte (c), eosinophil (d), basophil (e) and neutrophil/lymphocyte (f) ratio responses to an acute bout of resistance exercise in normoxia or hypoxia. Mean $\pm$ SD. * Significant difference between hypoxia and normoxia ($p < 0.05$).

compared to $98.0 \pm 1.7\%$ in normoxia. These SpO_2 levels were similar to other resistance training protocols in similar hypoxic conditions [17]. There was no difference in RPE between the hypoxic and normoxic groups, suggesting that the difficulty of hypoxic exercise was not greater than normoxic exercise. After performing the exercise session, 10 out of the 13 participants thought that they were randomised to the hypoxic group, suggesting that the participants were successfully blinded to their environmental condition.

Generally speaking, hypoxia is thought to elicit a greater relative exercise intensity than normoxia [22, 23], which in turn increases metabolic stress, activates sympathetic pathways and induces a greater immune response [21]. However, in the present study, blood glucose, blood lactate and heart rate were not significantly different between experimental groups, despite evidence that acute normobaric hypoxia enhances glucose disposal into skeletal muscle through contraction-mediated pathways [44]. Furthermore, the blood lactate result was not consistent with most other resistance training protocols where lactate is significantly elevated following hypoxic exercise [45, 46]. It is possible that the high training intensity and load used in our study elicited a near-maximal blood lactate response and therefore the additional stimulus of hypoxia was marginal. Blood lactate peaked at approximately 14 mmol/L^{-1} in hypoxia immediately post-exercise, compared to peaks of approximately $6\text{--}9 \text{ mmol/L}^{-1}$ in hypoxic training studies that used a similar exercise intensity [28, 47, 48]. Therefore, relative exercise intensity may not have significantly contributed to the immune response in this study. The immune response to hypoxic resistance exercise is likely

multifaceted, with possible contributions from other hormonal factors (Eg. growth hormone) and the activation of immune-related pathways such as HIF-1 and NF- κ B.

CONCLUSIONS

Exposure to normobaric hypoxia during an acute bout of resistance exercise increases the neutrophil response at 120 and 180 minutes post-exercise compared to normoxia. Further research is required to examine the causes and functional implications of the hypoxia-induced neutrocytosis. No other leukocyte populations were affected by hypoxic resistance exercise, suggesting that in healthy males, the addition of hypoxia during resistance training may allow positive training adaptations without negatively impacting immune function. However, caution should be applied when using more severe hypoxic stimuli and longer hypoxic exposure times than the current study, as further investigation is needed to assess these chronic impacts. Similarly, the long-term effects on leukocytes must be determined to conclusively state that hypoxia is a safe and effective tool for exercise prescription.

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Conflict of interest declaration

The authors declare no conflict of interest.

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Effects of pitch size on soccer players' physiological, physical, technical, and tactical responses during small-sided games: a meta-analytical comparison

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ABSTRACT: One of the most often-used task constraints in designing small-sided games (SSGs) is the manipulation of pitch size to promote increases or decreases in the relative area per player. Such adjustments cause changes in the acute responses during SSGs. This systematic review with meta-analysis aimed to compare the effects of smaller vs. larger pitch sizes on soccer players' physiological, physical, technical, and tactical responses during SSGs. Comparisons between smaller and larger pitches were not considered based on a specific size, but also between using at least two dimensions in the same comparative study, aiming to understand differences between using smaller and larger (independently of the specific dimensions). The data sources utilized were PubMed, PsycINFO, Scielo, Scopus, SPORTDiscus, and Web of Science. The database search initially yielded 249 titles. From those, 41 articles were eligible for the systematic review and meta-analysis. Results revealed that, compared to smaller pitches, SSGs played on larger pitches induced greater values for heart rate ($p < 0.001$; ES = 0.50), rate of perceived exertion ($p < 0.001$; ES = 0.70), total distance ($p < 0.001$; ES = 1.95), high-speed running ($p < 0.001$; ES = 1.20), stretch index ($p < 0.001$; ES = 1.02) and surface area ($p < 0.001$; ES = 1.54). No significant differences were found between pitch size regarding the numbers of accelerations ($p = 0.232$; ES = 0.45), decelerations ($p = 0.111$; ES = 0.85), passes ($p = 0.897$; ES = 0.02), dribbles ($p = 0.823$; ES = -0.05), or positional centroid ($p = 0.053$; ES = 0.56). Larger pitch sizes can be implemented as a meaningful task constraint to increase the internal and external load experienced by soccer players during SSGs, as well as to increase the dispersion of players while acting together. These results were found independent of format and age group.

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INTRODUCTION

Soccer is classified as an intermittent exercise [1] in which the effort exerted depends on the dynamic of the game [2]. Considering the complexity of soccer, performance is multidimensional—fitness status [3], technical skill [4], and tactical knowledge and execution [5] are just a few examples of parts that act concurrently to explain the ultimate outcome. Naturally, the aforementioned multidimensional factors also explain the physiological, physical, technical, and tactical responses of players training and matches [6].

The use of drill-based games such as small-sided games (SSGs), also known as small-sided conditioned games, have become popular since they reflect the multidimensional stimulus provided by matches while allowing the coach to alter players' specific responses by manipulating various task constraints [7–9]. SSGs can be thought of as adjusted versions of official games in which coaches adjust specific constraints (or conditions) to change the behaviors of the players [10]. Among the most common adjustments used by coaches is the pitch configuration, as implementing smaller vs. larger pitch sizes impacts players' behaviors [11].

Changing the pitch size (while keeping the same format of play) causes variations in relative area per player (calculated as the area of the pitch divided by the number of outfield players involved in the game) [12]. This manipulation is one of the main concerns while using SSGs since different relative areas per player for the same format change the players' responses [13, 14]. Decreasing or increasing the relative area per player can initiate changes in physiological responses, physical demands, technical execution, and tactical behavior (as well as collective dynamics) [15–17]. If the information is not systematized (e.g., using a meta-analysis), it is difficult to understand the true effects of changing the pitch size since different moderators may compromise the findings.

Most of the original studies testing the effects of different pitch sizes on players' responses have focused on specific measures within the main outcomes of physiological, physical, technical, and tactical responses [11]. In the case of physiological responses, the most often-used measures are heart rate, rate of perceived exertion (RPE), and blood lactate concentrations [14]. In the case of physical demands, microelectromechanical devices (e.g., Global Navigation Satellite System, Inertial Measurement Units) are usually used to assess the total distance covered, distances covered at different speed thresholds, and the number of accelerations/decelerations performed by players [18]. For technical execution, observational analysis is usually conducted to identify the number and accuracy of passes, receptions, dribbles, and shots during SSGs [15, 19]. Finally, in the case of tactical behavior also observational analysis is used to identify the accuracy of attacking and defensive behaviors or using bidimensional data to analyze measures related to the team's spread or dispersion in the pitch [20].

Since adjustments in pitch size for the same format of play (e.g., 4 vs. 4 played on a smaller pitch (50 m² per player) vs. a larger pitch (100 m² per player) induce changes in players' responses, it

may be determinant to identify the impact of those changes. This allows coaches to understand the consequences of their adjustments on players' responses and identify the most appropriate pitch sizes for specific objectives. Although systematic reviews have been conducted on the topic of SSGs (particularly summarizing the evidence regarding the impact of pitch size manipulation on players' responses [7–9, 21, 22], no meta-analysis has been performed to identify the effects of smaller vs. larger pitch sizes on players' responses. A meta-analysis may provide consistent evidence about the magnitudes of changes occurring between smaller and larger pitch sizes. Therefore, the purpose of this systematic review with meta-analysis was to compare the effects of smaller vs. larger pitch sizes on physiological, physical, technical, and tactical responses during small-sided soccer games.

MATERIALS AND METHODS

This systematic review and meta-analysis followed the Cochrane Collaboration [23], PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines [24] and guidelines for performing systematic review in sports sciences [25]. The PICOS approach (Population, Intervention, Comparator, Outcomes, Study design) was followed: (P) soccer players from any age-group, sex or skill, without injury, illness or other clinical condition; (I) smaller pitch sizes using any format of play (number of players involved) or other task condition; (C) larger pitch sizes using any format of play (number of players involved) or other task condition (keeping the same experimental conditions of smaller formats); (O) mean and standard deviation (SD) values in both pitch sizes for, at least, one of the following main outcomes: physiological responses, physical responses, technical actions and tactical behaviors; and (S) counterbalanced cross-over design. Important to highlight those comparisons between smaller and larger pitches were not considered based on a specific size, but also between using at least two dimensions in the same comparative study, aiming to understand differences between using smaller and larger (independently of the specific dimensions). The protocol was registered with the International Platform of Registered Systematic Review and Meta-Analysis Protocols with the number INPLASY202140016 and the DOI number 10.37766/inplasy2021.4.0016.

Eligibility criteria

Inclusion and exclusion criteria for this systematic review and meta-analysis can be found in table 1.

Duplicates were identified using a reference manager software (EndNote™ X9, Clarivate Analytics, Philadelphia, PA, USA). Two authors (FMC and HS) independently performed screening of the title, abstract and reference list of each study to locate potentially relevant studies. Additionally, they reviewed the full version of the papers in detail to identify articles that met the selection criteria and those that were excluded. A discussion was made in the cases of discrepancies regarding the selection process with the participation of a third author (AFS).

TABLE 1. Inclusion and exclusion criteria

Item	Inclusion criteria	Exclusion criteria
Population	Soccer players from any age-group, sex or skill, without injury, illness or other clinical condition.	Other sports than soccer (e.g., futsal or football indoor, beach soccer, American football, Australian football, basketball, handball, volleyball, hockey).
Intervention	Smaller pitch sizes using any format of play (number of players involved) or other task condition. The following conditions were ensured: • The same pitch size was repeated at least two times (two repetitions) for the same players; • The smaller pitch size was extracted from the lowest relative pitch area (i.e., in case of studies comparing $\geq$ three pitch sizes for the same format or condition, only the smallest pitch size was extracted); • The same experimental conditions between smaller and larger pitch sizes were ensured (i.e., same teams, same players, same time duration, same task constraints).	• The same pitch size was applied in only one repetition; • Smaller and larger pitch sizes conditions were not applied with same contextual and experimental conditions.
Comparator	Larger pitch sizes using any format of play (number of players involved) or other task condition. The following conditions were ensured: • The same pitch size was repeated at least two times (two repetitions) for the same players; • The larger pitch size was extracted from the greatest relative pitch area (i.e., in case of studies comparing $\geq$ three pitch sizes for the same format or condition, only the largest pitch size was extracted); • The same experimental conditions between smaller and larger pitch sizes were ensured (i.e., same teams, same players, same time duration, same task constraints).	• The same pitch size was applied in only one repetition; • Smaller and larger pitch sizes conditions were not applied with same contextual and experimental conditions.
Outcome	At least one measure of the following possibilities: • Physiological responses (e.g., heart rate, blood lactate concentrations or rated of perceived exertion); • Physical demands (e.g., total distance, distances covered at different speed thresholds, acceleration/decelerations); • Technical execution (e.g., passes, receptions, shots); • Tactical behavior (e.g., attacking or defensive tactical principles, collective organization measures)	Other outcomes than those related to immediate physiological and physical, technical or tactical responses (e.g., fatigue tests, well-being tests).
Study design	A counterbalanced cross-over design.	Non-counterbalanced cross-over design studies.
Additional criteria	Peer reviewed, original, full-text studies written in English, Portuguese and/or Spanish.	Written in other language than those selected (English, Portuguese and/or Spanish). Reviews, letters to editors, trial registrations, proposals for protocols, editorials, book chapters, conference abstracts.

Information sources

Electronic databases (PubMed, PsycINFO, Scielo, Scopus, SPORT-Discus and Web of Science) were searched for relevant publications prior to the February 18, 2021. Keywords and synonyms were entered in various combinations in all fields: (“soccer” OR “football”) AND (“small-sided games” OR “conditioned games” OR “SSG” OR “drill-based games” OR “small-sided conditioned games”) AND (“pitch” OR “field”). Additionally, the reference lists of the included studies retrieved were manually searched to identify potentially eligible studies not captured by the electronic searches. Finally, an external expert in small-sided games with more than 10 publications in the last five years was contacted to verify the final list of references included in this systematic review and to indicate if there was any study that was not detected through our research.

Extraction of data

A data extraction sheet, adapted from the Cochrane Consumers and Communication Review Group's data extraction template [26], was used to assess inclusion requirements and subsequently tested on ten randomly selected studies (i.e., pilot testing). This process was conducted by two independent reviewers (FMC and HS). Any disagreement regarding study eligibility was resolved in a discussion between both reviewers and a third author (AFS). Full text articles excluded, with reasons, were recorded. The records were registered in a form created in Microsoft Excel (Microsoft Corporation, Readmon, WA, USA).

Data items

Aiming to establish consistency in data analyzing and reporting, only measures that were analyzed three or more times for different articles were included. For physiological responses the following list of measures were extracted, and following this order of priority: (i) heart rate responses (e.g., absolute or relative); (ii) blood lactate concentrations; and (iii) RPE. For physical demands, the following list of measures were extracted and following this order of priority: (i) total distance covered; (ii) distance covered at different speed thresholds; (iii) accelerations and decelerations (number at different intensity thresholds); and (iv) mechanical workload measures (derived from inertial measurement unit). For technical execution the following list of measures were extracted and following this order of priority: (i) individual passes (total number, relative number considering accuracy); (ii) individual receptions (total number, relative number considering accuracy); (iii) individual shots (total number, relative number considering accuracy); and (iv) individual dribbles (total number, relative number considering accuracy). For tactical behavior the following list of measures were extracted and following this order of priority: (i) individual attacking tactical behavior; (ii) individual defensive tactical behavior; (iii) collective measure of dispersion. Tests and instruments used for measuring the outcomes were also extracted. Mean and SD for each outcome extracted in smaller and larger pitch sizes were collected. Additionally, the following information was extracted from

the included studies: (i) number of participants (n), age-group (years), competitive level (e.g., elite, professional, amateur) and sex; (ii) the SSGs format (e.g., 5 vs 5; 6 vs 6), pitch size and relative area per player; (iii) regimen of intervention (work duration, work intensity, modality, relief duration, relief intensity, repetitions and series, between-set recovery).

Assessment of methodological quality

The methodological index for non-randomized studies (MINORS) was used for assessing the methodological quality of the included studies [27]. This scale classifies twelve items of the original articles, in which a score of zero indicates the absence of a report, the score of one represents that report is inadequate and two points indicate that the report is adequate. Two of the authors (HS and MRG) independently assessed the methodological quality. Any disagreement in the rating was resolved through discussion and by a third author (FMC).

Summary measures, synthesis of results, and publication bias

Although two studies can be used in meta-analyses [28], considering reduced sample sizes are common in the sports science literature [29], particularly SSG studies [30], analysis and interpretation of results in this systematic review and meta-analysis were only conducted in the case of at least three study groups provided mean and standard-deviation for smaller and larger pitch sizes for the same measure. Means and SD for dependent variables were used to calculate effect sizes (ES; Hedge's *g*) for each outcome in the smaller and larger pitch sizes. In case means and SDs were not available, they were obtained from 95% confidence intervals (CIs) or standard error of mean (SEM), using Cochrane's RevMan Calculator. Data were standardized using post-intervention SD values. The random-effects model was used to account for differences between studies that might impact the SSG-based effect [31, 32]. The ES values are presented with 95% CI. Calculated ES were interpreted using the following scale: < 0.2, trivial; 0.2–0.6, small; > 0.6–1.2, moderate; > 1.2–2.0, large; > 2.0–4.0, very large; > 4.0, extremely large [33]. Heterogeneity was assessed using the I^2 statistic, with values of < 25%, 25–75%, and > 75% considered to represent low, moderate, and high levels of heterogeneity, respectively [34]. The risk of bias was explored using the extended Egger's test [35]. To adjust for publication bias, a sensitivity analysis was conducted using the trim and fill method [36], with LO as the default estimator for the number of missing studies [37]. All analyses were carried out using the Comprehensive Meta-Analysis software (version 2; Biostat, Englewood, NJ, USA). Statistical significance was set at $p \leq 0.05$.

Moderator analyses

Using a random-effects model and independent computed single factor analysis, potential sources of heterogeneity likely to influence the effects of SSGs were selected *a priori*. As the responses to SSGs may be affected by the format of play, sub-group analysis considered

the following the groups of formats of play [38]: (a) duels (1vs.1); (b) small formats (2vs.2, 3vs.3 and 4vs.4); (c) medium formats (5vs.5, 6vs.6, 7vs.7, 8vs.8); and (d) large formats (9vs.9, 10vs.10, 11vs.11). Additionally, information about age-group was also considered as moderator (young & youth < 23 years old since is the last category of youth in soccer; adults > 23 years old).

RESULTS

Study identification and selection

The searching of databases identified an initial 249 titles. Duplicates (160 references) were subsequently removed either automatically or

manually. The remaining 89 articles were screened. After reading full texts, a further 47 studies were excluded owing to a number of reasons: studies not performed in soccer, studies that not compare two pitch size (or not with the same condition), and studies not reporting physical, physiological, technical, or tactical outcomes. Therefore, 42 articles were eligible for the systematic review and 41 for the meta-analysis (Figure 1). The included articles provided mean and SD for smaller and larger pitch sizes data for at least one main outcome.

Methodological quality

The assessment of the included studies can be found in Table 2.

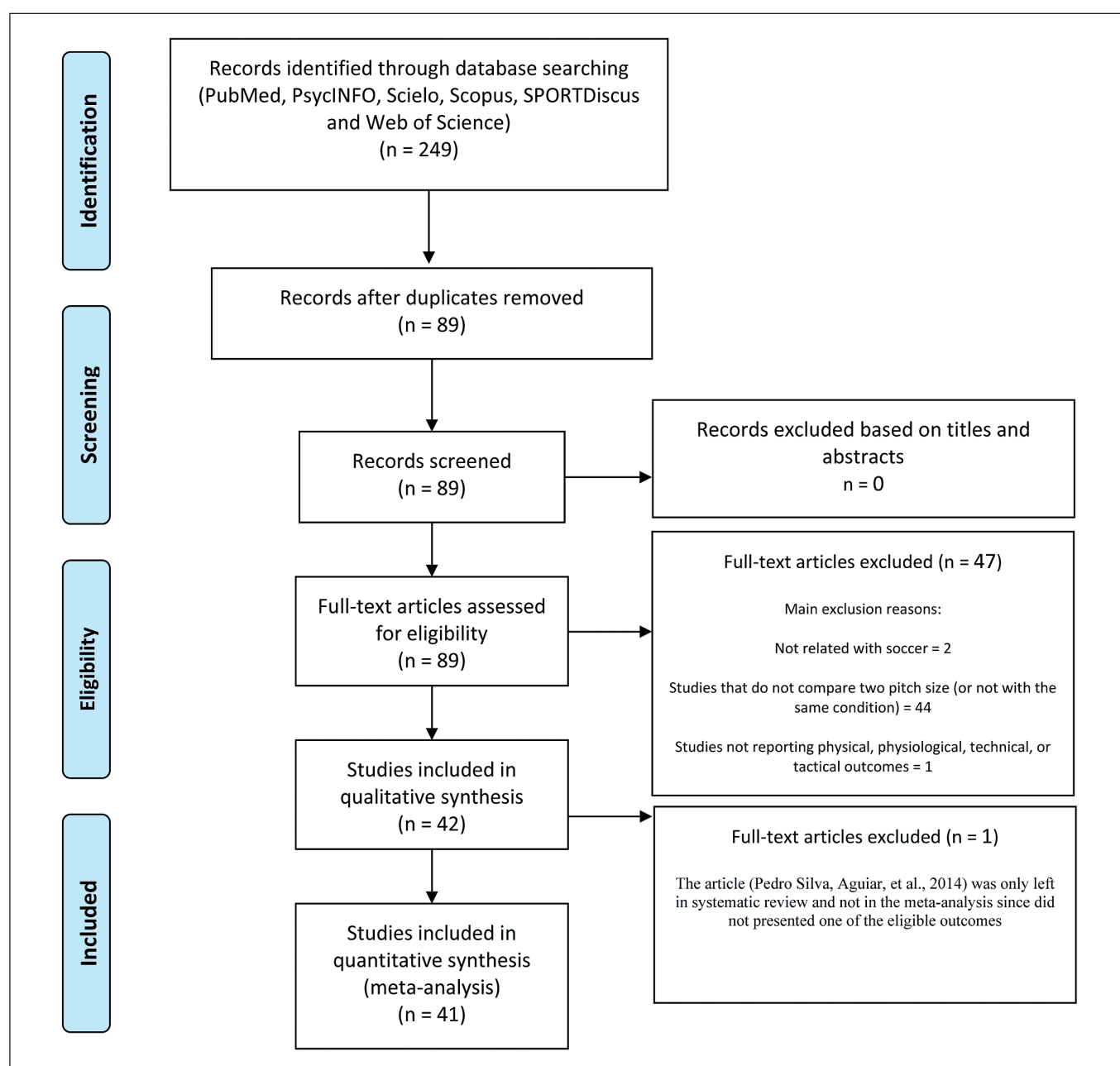


FIG. 1. PRISMA flow diagram highlighting the selection process for studies.

TABLE 2. Assessment of studies methodological quality using the MINORS scale

Study	1*	2*	3*	4*	5*	6*	7*	8*	9*	10*	11*	12*	Total** (%)
[71]	1	1	1	1	0	1	1	1	-	1	1	1	90
[72]	1	0	1	1	0	0	1	1	-	1	0	1	64
[73]	1	0	1	1	0	1	1	1	-	1	0	1	72
[74]	1	0	1	1	0	1	1	1	-	1	1	1	81
[40]	1	0	1	1	0	0	1	1	-	1	0	1	64
[18]	1	1	1	1	1	0	1	1	-	1	1	1	90
[75]	1	0	1	1	0	1	1	1	-	1	0	1	72
[76]	1	1	1	1	0	0	1	1	-	1	0	1	72
[77]	1	0	1	1	0	0	1	1	-	1	1	1	72
[14]	1	0	1	1	0	1	1	1	-	1	1	1	81
[13]	1	1	1	1	0	1	1	1	-	1	1	1	90
[78]	1	0	1	1	0	1	1	1	-	1	1	1	81
[79]	1	1	1	1	0	1	1	1	-	1	1	1	90
[80]	1	1	1	1	0	0	1	1	-	1	1	1	81
[68]	1	0	1	1	0	0	1	1	-	1	0	1	64
[81]	1	0	1	1	0	0	1	1	-	1	0	1	64
[82]	1	0	1	1	0	1	1	1	-	1	1	1	81
[69]	1	0	1	1	0	0	1	1	-	1	0	1	64
[83]	1	1	1	1	0	1	1	1	-	1	1	1	90
[84]	1	0	1	1	0	0	1	1	-	1	1	1	72
[85]	1	0	1	1	0	1	1	1	-	1	1	1	81
[61]	1	1	1	1	0	0	1	1	-	1	1	1	81
[86]	1	0	1	1	0	1	1	1	-	1	0	1	72
[87]	1	0	1	1	0	1	1	1	-	1	1	1	81
[88]	1	0	1	1	0	1	1	1	-	1	1	1	81
[39]	1	0	1	1	1	1	1	1	-	1	1	1	91
[17]	1	0	1	1	0	0	1	1	-	1	0	1	64
[89]	1	0	1	1	0	1	1	1	-	1	1	1	81
[19]	1	1	1	1	0	1	1	1	-	1	1	1	90
[90]	1	1	1	1	0	0	1	0	-	1	1	1	73
[91]	1	1	1	1	0	1	1	1	-	1	1	1	91
[92]	1	0	1	1	0	0	1	1	-	1	0	1	64
[62]	1	0	1	1	0	0	1	1	-	1	1	1	72
[93]	1	1	1	1	0	0	1	1	-	1	1	1	81
[66]	1	1	1	1	0	0	1	1	-	1	1	1	81
[94]	1	1	1	1	0	0	1	1	-	1	0	1	72
[95]	1	0	1	1	0	1	1	1	-	1	0	1	72
[96]	1	0	1	1	0	0	1	1	-	1	0	1	64
[20]	1	0	1	1	0	0	1	1	-	1	1	1	72
[58]	1	0	1	1	0	0	1	1	-	1	1	1	72
[97]	1	0	1	1	0	1	1	1	-	1	0	1	72
[98]	1	0	1	1	0	0	1	1	-	1	0	1	64

*: MINORS scale items number; N..1: A clearly study aimed; N.. 2: Inclusion of consecutive patients; N.. 3: Prospective collection of data; N.. 4: Endpoints appropriate to the aim of the study; N.. 5: Unbiased assessment of the study endpoint; N.. 6: Follow-up period appropriate to the aim of the study; N.. 7: Loss to follow less than 5%; N.. 8: Prospective calculation of the study size; N.. 9: An adequate control group; N..10: Contemporary groups; N.. 11: Baseline equivalence of groups; N.. 12: Adequate statistical analyses; **: the total number of points from a possible maximal of 24.

Study characteristics

The characteristics of the included studies in the meta-analysis can be found in Table 3. Additionally, the details of the SSGs-interventions can be found in Table 4.

Smaller vs. larger pitch sizes during SSG: effects on physiological responses

A summary of the included studies and results of physiological responses (HR and RPE) reported in smaller and larger SSGs are provided in Table 5.

TABLE 3. Characteristics of the included studies and outcomes extracted.

Study	N	Mean + SD age (y)	Experience (y)	Sex	Randomization of SSGs order	Design	Variables assessed in the study and tendency	Tests or tools used	Outcome extracted
[71]	10 recreational players	31.7 ± 7.6	0.25–0.50	Male	Yes	Repeated measures	Mean HR; peak HR; RPE; HR zones; ball possession; dribbling; passes; tackles; shots. <i>Pitch effect:</i> ball possessions and unsuccessful passes were higher on a small pitch.	HR monitor; 15-point Borg scale; video cameras	Physiological responses; Technical actions
[72]	16 youth elite players	16.9 ± 0.3	-	Male	Yes	Repeated measures	Maximum velocity; mean velocity; distance covered at several velocities; accelerations. <i>Pitch effect:</i> more HI distance is covered in higher SSG.	GPS	Physical responses
[73]	9 professional soccer players	26.2 ± 3.7	5.5	Male	Yes	Repeated measures	Maximum velocity; distance/min; distance covered at several velocities; mean HR; peak HR; HR zones. <i>Pitch effect:</i> higher physical values in larger areas.	GPS; HR monitor	Physical responses; Physiological responses
[74]	20 amateur soccer players	21.0 ± 5.0	11	Male	No	Repeated measures	Peak HR; RPE; TD; maximum velocity; player load; accelerations/deceleration; change of directions. <i>Pitch effect:</i> increasing the pitch length had a greater effect compared to increasing the pitch width.	HR monitor; 10-point Borg scale; GPS	Physiological responses; Physical responses
[40]	10 male youth players	15.5 ± 0.5	7.5	Male	Yes	Repeated measures	Effective playing time; start of play; contact surface; successful actions. <i>Pitch effect:</i> increase frequency of motor actions when pitch is reduced.	Video camera	Technical actions
[18]	10 male youth players	15.5 ± 0.5	7.5	Male	Yes	Repeated measures	Effective playing time; Peak HR; HR zones; RPE; TD; distance/min; distance covered at several velocities; work-rest ratio; sprint frequency; several technical actions. <i>Pitch effect:</i> increasing the pitch size increase the effective playing time, the physical and physiological workload and the RPE, but reduce the frequency of motor actions.	HR monitor; 10-point Borg scale; GPS; video camera	Physiological responses; Physical responses; Technical actions
[75]	19 professional players	17.1 ± 0.3	-	Male	Yes	Repeated measures	TD; HI velocity; HI accelerations; HI decelerations; HI metabolic power; Lactate; Mean HR; Peak HR; RPE. <i>Pitch effect:</i> Lower SSG elicit lower external load values than higher SSGs	GPS; HR monitor; lactate portable analyser; 10-point Borg scale	Physical responses; Physiological responses

TABLE 3. Continue.

Study	N	Mean + SD age (y)	Experience (y)	Sex	Randomization of SSGs order	Design	Variables assessed in the study and tendency	Tests or tools used	Outcome extracted
[76]	28 youth players	U13: 13.5 ± 0.3 U14: 14.3 ± 0.3	> 3	Male	Yes	Repeated measures	TD; distance covered at several velocities; player load; exertion index; work-rest ratio; Maximum velocity. <i>Pitch effect:</i> increasing pitch size elicit higher responses in both groups.	Accelerometer; GPS	Physical responses
[77]	24 youth elite players	13.3 ± 0.5	> 3	Male	Yes	Repeated measures	TD; distance covered at several velocities; player load; exertion index; work-rest ratio; Maximum velocity; Mean HR; Peak HR; RPE; HR zones. <i>Pitch effect:</i> higher pitch sizes are associated with increases in TD, work-rest ratio, player load, Peak HR and in the distance covered at 8 km/h.	GPS; HR monitor; 10-point Borg scale	Physical responses; Physiological responses
[14]	44 youth players	U12: 12.1 ± 0.4 U13: 13.3 ± 0.5	> 1	Male	No	Repeated measures	TD; distance covered at several velocities; player load; exertion index; work-rest ratio; Maximum velocity; Mean HR; Peak HR; RPE; HR zones. <i>Pitch effect:</i> higher pitch size is related with greater responses.	GPS; HR monitor; 10-point Borg scale	Physical responses; Physiological responses
[13]	28 youth players	U13: 13.5 ± 0.3 U14: 14.3 ± 0.3	> 3	Male	No	Repeated measures	Team length; width length; convex hull; stretch index; distance between centroids; length of both teams; width of both teams; convex hull of both teams; stretch index of both teams. <i>Pitch effect:</i> higher pitch size is related with greater tactical responses.	GPS	Tactical responses
[78]	24 youth players	11.8 ± 0.3	> 3	Male	Teams configuration	Repeated measures	TD; distance covered at several velocities; number of sprints; Maximum velocity; accelerations; decelerations; body impacts. <i>Pitch effect:</i> increasing pitch size elicit higher responses.	GPS	Physical responses
[79]	10 youth players	14.8 ± 0.6	> 3	Male	No	Repeated measures	TD; distance covered at several velocities; number of sprints; Maximum velocity; Mean HR; Peak HR. <i>Pitch effect:</i> increasing pitch size elicit higher responses.	GPS; HR monitor	Physical responses; Physiological responses
[80]	20 youth players	14.9 ± 0.6	> 3	Male	No	Repeated measures	TD; distance covered at several velocities; number of sprints; Maximum velocity; accelerations; decelerations; body impacts. <i>Pitch effect:</i> larger SSG demanded a higher external load in comparison with shorter SSG.	GPS	Physical responses

TABLE 3. Continue.

Study	N	Mean + SD age (y)	Experience (y)	Sex	Randomization of SSGs order	Design	Variables assessed in the study and tendency	Tests or tools used	Outcome extracted
[68]	10 amateur players	23.4 ± 3.9	-	Male	No	Repeated measures	TD; distance covered at several velocities; number of sprints; spatial exploration index. <i>Pitch effect:</i> increasing pitch size elicit higher responses.	GPS	Physical responses; Tactical responses
[81]	10 amateur players	23.4 ± 3.9	-	Male	No	Repeated measures	Centroid; stretch index. <i>Pitch effect:</i> increasing pitch size elicit higher tactical responses.	GPS	Tactical responses
[82]	40 international players	25.3 ± 2.4	-	Male	Yes	Repeated measures	%HR reserve; Peak HR; RPE; lactate; TD, TD in sprinting; TD in HI; duels, passes, balls lost; ball possessions. <i>Pitch effect:</i> SSG elicit higher demands compared to friendly matches, except for lactate, successful passes and ball possessions.	HR monitor; GPS; semi-automatic multiple camera system; lactate portable analyser; 10-point Borg scale.	Physical responses; Physiological responses; Technical responses
[69]	10 amateur players	22.0 ± 3.0	-	Male	No	Repeated measures	Centroid; area; inter-team distance in longitudinal and lateral directions; distance of centroids. <i>Pitch effect:</i> increasing pitch size elicit greater area and distances.	LPS	Tactical responses
[83]	11 youth players	16.3 ± 0.6	> 6	Male	No	Repeated measured	Metabolic power; TD; HI demands. <i>Pitch effect:</i> increasing pitch size elicit higher responses.	GPS	Physical responses
[84]	8 amateur players	27.2 ± 3.1	12	Male	No	Repeated measured	Shots; passes; accurate passes; inaccurate passes; dribbles; interceptions; tackles. <i>Pitch effect:</i> no influence of pitch size on technical actions.	Digital cameras.	Technical responses
[85]	16 youth players	13.2 ± 0.6	> 3	Male	Yes	Repeated measures	HR; RPE: lactate. <i>Pitch effect:</i> higher physiological responses in larger pitch size.	HR monitor; lactate portable analyser; 10-point Borg scale.	Physiological responses
[61]	8 university-level players	20.0 ± 1.0	> 5	Male	Yes	Repeated measures	TD; HI distance; sprint distance; accelerations; decelerations; Peak HR; Maximum HR; pass; tackle; header; turn; interception; dribbling; shots. <i>Pitch effect:</i> increasing pitch size elicit higher responses.	GPS; HR monitor; video camera.	Physical responses; Physiological responses; Technical responses
[86]	29 junior players	18.1 ± 1.3	-	Male	No	Repeated measures	TD; Peak HR; HR zones; RPE. <i>Pitch effect:</i> increasing pitch size elicit higher physiological responses.	Video manual motion tracker; HR monitor; 10-point Borg scale	Physical responses; Physiological responses

TABLE 3. Continue.

Study	N	Mean + SD age (y)	Experience (y)	Sex	Randomization of SSGs order	Design	Variables assessed in the study and tendency	Tests or tools used	Outcome extracted
[87]	3 youth goalkeepers	16.6 ± 0.9	7.3	Male	No	Repeated measures	Goalkeeper's actions: Goal kick; direct free kick; indirect free kick; pass by hand; pass by foot; length; direction; area; save; deflection; clear-out; Open palm; parry; fly; 1-on-1; screen; zone intervention. <i>Pitch effect:</i> decreasing pitch size elicit higher goalkeepers' technical responses.	Observational tool	Technical responses; Tactical responses
[88]	3 goalkeepers	24.5 ± 7.2	11	Male	No	Repeated measures	TD; spatial exploration index; predictive ellipse area; standard ellipse area; distance covered at different velocities; accelerations; decelerations. <i>Pitch effect:</i> increasing pitch size elicit lower goalkeepers' physical responses and higher tactical responses.	GPS	Physical responses; Tactical responses
[39]	149 young players	12.0 ± 0.4	-	Male	Yes	Repeated measures	Field players and goalkeepers actions: Ball touches; Passes; Shots; TD in play; TD out play Distance covered at different velocities. <i>Pitch effect:</i> pitch size influences on physical and technical responses of field players and goalkeepers.	Semi-automated multi-camera system	Physical responses; Technical responses
[17]	8 elite players	18.0 ± 1	-	Male	Yes	Repeated measures	Mean HR; pass; receive; turn; dribble; header; tackle; interception; shot; target pass. <i>Pitch effect:</i> While pitch size does not affect physiological responses, increasing pitch size elicit higher shots and tackles.	HR monitor; video camera	Physiological responses; Technical responses
[89]	16 youth players	14.2 ± 0.6	5.5	Male	Yes	Repeated measures	Mean HR; %HRmax; RPE. <i>Pitch effect:</i> Increasing pitch size elicit higher physiological responses.	HR monitor; 10-point Borg scale	Physiological responses
[19]	48 youth players	U13 U14	-	Male	Teams' composition	Repeated measures	TD; distance covered at different velocities; Peak HR; Mean HR. <i>Pitch effect:</i> no influence of pitch size on physical and physiological demands	GPS; HR monitor	Physiological responses; Physical responses
[90]	16 elite players	19.6 ± 2.0	5.8	Female	Yes	Repeated measures	TD; body loads, high-intensity distance. <i>Pitch effect:</i> Increasing pitch size elicit higher physical responses.	GPS	Physical responses
[91]	16 elite players	19.6 ± 2.0	5.8	Female	Yes	Repeated measures	Peak HR; Mean HR; %HRmean; HR zones; VAS scales. <i>Pitch effect:</i> Increasing pitch size elicit higher physiological responses at low intensities.	HR monitor; questionnaire	Physiological responses

TABLE 3. Continue.

Study	N	Mean + SD age (y)	Experience (y)	Sex	Randomization of SSGs order	Design	Variables assessed in the study and tendency	Tests or tools used	Outcome extracted
[92]	10 youth players	13.0 ± 0.3	-	Male	No	Repeated measures	HR HI; passes; dribbles; possessions. <i>Pitch effect:</i> No influence in HR HI and increasing pitch size elicit higher lower possessions and higher ball touches.	HR monitor; Video camera	Physiological responses; Technical responses
[62]	23 university players	22.3 ± 2.0	12.1	Male	Teams' composition	Repeated measures	TD; distance covered at different velocities; sprints; maximum sprint speed; ball contacts; maximum passing speed; RPE. <i>Pitch effect:</i> increasing pitch size elicit higher physical responses.	GPS; 10-point Borg scale; Play Soccer system	Physical responses; Physiological responses; Technical responses
[93]	52 youth players	U11: 10.0 ± 0.7 U15: 14.0 ± 1.3 U23: 21.0 ± 1.6	1.0 3.0 6.5	Male	-	Repeated measures	TD; distance covered at different velocities; sprints; maximum sprint speed; ball contacts; maximum passing speed; RPE. <i>Pitch effect:</i> increasing pitch size elicit higher physical responses and influence on technical actions.	GPS; 10-point Borg scale; Play Soccer system	Physical responses; Physiological responses; Technical responses
[66]	148 youth players	U12: 12.5 ± 0.5 U14: 14.4 ± 0.5 U16: 16.6 ± 3.2 U18: 17.9 ± 1.0	-	Male	Teams' composition	Repeated measures	TD; HI distance; sprints; inter-team distance, LPW-ratio, surface area, stretch indices, goalkeeper-defender distance; tactical variability. <i>Pitch effect:</i> increasing pitch size elicit higher physical responses and intra-team and inter-team distances and tactical variability.	LPS	Physical responses; Tactical responses
[94]	10 recreational players	20.1 ± 1.1	-	Male	-	Repeated measures	Mean HR; %HRmax; HR zones; TD; distance covered at different velocities; maximal speed; efforts; player load. <i>Pitch effect:</i> increasing pitch size elicit higher physiological and physical responses.	HR monitor; GPS	Physiological responses; Physical responses
[95]	20 amateur players	24.5 ± 4.1	15	Male	Yes	Repeated measures	Mean HR; Blood lactate; RPE. <i>Pitch effect:</i> increasing pitch size elicit higher physiological responses.	HR monitor; lactate portable analyser	Physiological responses
[96]	86 youth players	U10 U13	-	Male	Yes	Repeated measures	Mean HR; Peak HR; HR zones; TD; efforts; distance covered at different velocities; player load; number of technical actions; successful actions; success rate. <i>Pitch effect:</i> increasing pitch size elicit higher physical responses and lower technical involvement.	HR monitor; GPS; video camera	Physiological responses; Physical responses; Technical responses

TABLE 3. Continue.

Study	N	Mean + SD age (y)	Experience (y)	Sex	Randomization of SSGs order	Design	Variables assessed in the study and tendency	Tests or tools used	Outcome extracted
[20]	20 youth players	16.2 ± 0.6 ^a 15.6 ± 0.5	6.6 6.2	Male	No	Repeated measures	Spatial distribution variability; Shannon entropy; player-to-locus distance; coefficient of variation; sample entropy. <i>Pitch effect:</i> manipulating pitch size influence on movement variability.	GPS	Tactical responses. The outcomes were not obtained for meta-analysis since none was within the information extracted, thus keeping only in the systematic review
[58]	20 youth players	16.2 ± 0.6 15.6 ± 0.5	6.6 6.2	Male	No	Repeated measures	Team separateness; effective playing space; length-width ratio; average mutual information in longitudinal direction; average mutual information in lateral direction; sample entropy of distance to nearest opponent. <i>Pitch effect:</i> manipulating pitch size influence on tactical responses.	GPS	Tactical responses
[97]	24 youth players	14.5 ± 0.5	6.1	Male	Yes	Repeated measures	Effective relative space per player; radius of free movement; spatial distribution variability; numerical relations. <i>Pitch effect:</i> manipulating pitch size influence on spatial distributions and numerical relations.	GPS	Tactical responses
[98]	15 amateur players	21.9 ± 2.0	9.9	Male	Teams' composition	Repeated measures	Interpersonal distance attackers and defenders; distance to intercept a shot; distance to intercept a pass. <i>Pitch effect:</i> increasing pitch size elicit greater opportunities to maintain ball possessions.	Video camera	Tactical responses
[69]	10 amateur players	22.0 ± 3.0	-	Male	No	Repeated measures	Centroid; area; inter-team distance in longitudinal and lateral directions; distance of centroids. <i>Pitch effect:</i> increasing pitch size elicit greater area and distances.	LPS	Tactical responses

Notes. GPS: global position system; HI: high-intensity; HR: heart rate; LPS: local positioning system; RPE: rate of perceived exertion; SD: standard-deviation; SSG: small-sided games; TD: total distance; VAS: visual analogue scale.

TABLE 4. Characteristics of small-sided games (SSGs) in the included studies.

Study	SSG formats	Smaller pitch (length × width)	Smaller pitch (area per player - m ²)	Larger pitch (length × width)	Larger pitch (area per player - m ²)	Larger/ Smaller (m ²)	Task conditions	Sets	Reps	Work duration	Between reps duration	Type of recovery
[71]	5vs.5 + GK 7vs.7 + GK	44 × 23 m	5 players: 101.2 m ² 7 players: 72.3 m ²	57 × 30 m	5 players: 171.0 m ² 7 players: 122.1 m ²	5 players: 1.7x 7 players: 1.7x	No throw-ins; restart the game as quickly as possible.	1	1	40 min	-	-
[72]	4vs.4	Not reported (125 m ²)	15.6 m ²	Not reported (300 m ²)	37.5 m ²	2.4x	Verbal encouragement.	1	1	8 min	-	-
[73]	6vs.6 + 1 6vs. + 1 + GK	20 × 30 m	43 m ²	50 × 40 m	154 m ²	3.6x	Two touch per player; verbal encouragement; restart the game as quickly as possible.	1	4	20 min	2 min	Passive
[74]	5vs.5 + GK	40 × 25 m	100 m ²	66 × 50 m	330 m ²	3.3x	No offside rule.	1	4	24 min	8 min	Passive
[40]	5vs.5 + GK	32 × 23 m	73.6 m ²	62 × 44 m	272.8 m ²	3.7x	No offside rule; verbal encouragement.	1	3	24 min	5 min	Passive
[18]	5vs.5 + GK	32 × 23 m	73.6 m ²	62 × 44 m	272.8 m ²	3.7x	No offside rule; verbal encouragement.	1	3	24 min	5 min	Passive
[75]	1vs.1	20 × 10 m	100 m ²	30 × 20 m	300 m ²	3.0x	Verbal encouragement; restart the game as quickly as possible; players free to score from any distance; no ball touches limit.	1	4	2 min	3 min	Active
[76]	7vs.7 + GK	30 × 40 m	100 m ²	60 × 40 m	200 m ²	2x	Restart the game as quickly as possible; offside rule.	1	4	28 min	4 min	Passive
[77]	7vs.7 + GK 9vs.9 + GK 11vs.11 + GK	45 × 27 m	100 m ²	100 × 60 m	300 m ²	3x	Verbal encouragement; restart the game as quickly as possible.	1	2	24 min	5 min	Passive
[14]	7vs.7 + GK 9vs.9 + GK 11vs.11 + GK	45 × 27 m	100 m ²	100 × 60 m	300 m ²	3x	Verbal encouragement; restart the game as quickly as possible.	1	2	24 min	5 min	Passive
[13]	7vs.7 + GK	30 × 40 m	100 m ²	60 × 40 m	200 m ²	2x	Restart the game as quickly as possible; offside rule.	1	4	28 min	4 min	Passive
[78]	6vs.6	22 × 13 m	25 m ²	39 × 23	75 m ²	3x	Restart the game as quickly as possible; verbal encouragement; offside rule in some configurations.	1	1	6 min	-	-
[79]	5vs.5 + GK	38 × 26 m	100 m ²	53 × 37 m	200 m ²	2x	Restart the game as quickly as possible; verbal encouragement.	1	6 4	4 min 6 min	2 min	Active
[80]	5vs.5 + GK	38 × 26 m	100 m ²	53 × 37 m	200 m ²	2x	Restart the game as quickly as possible; verbal encouragement; offside rule.	1	4	6 min	2 min	Active
[68]	11vs.11 + GK	54 × 68 m	167 m ²	108 × 68 m	334 m ²	2x	Official game rules	1	1	30 min	-	-
[81]	11vs.11 + GK	54 × 68 m	167 m ²	108 × 68 m	334 m ²	2x	Official game rules.	1	1	30 min	-	-
[82]	11vs.11 + GK	30 × 20 m	75 m ²	100 × 60 m	273 m ²	3.6x	Touch limitation (1, 2 or free).	1	4	16 min	3 min	Passive
[69]	4vs.4 + GK	24 × 16 m	38.4 m ²	30 × 20 m	60 m ²	1.6x	No offside rule; GK had 2-touch play; outfield players had to avoid long-range shots.	1	1	8 min	8 min	-
[83]	5vs.5 + GK	39 × 25 m	81 m ²	78 × 50 m	325 m ²	4x	No offside rule.	1	1	35 min	-	-

TABLE 4. Continue.

Study	SSG formats	Smaller pitch (length × width)	Smaller pitch (area per player -m ²)	Larger pitch (length × width)	Larger pitch (area per player -m ²)	Larger/ Smaller (m ²)	Task conditions	Sets	Reps	Work duration	Between reps duration	Type of recovery
[84]	4vs.4	34 × 26 m	111 m ²	40 × 30 m	150 m ²	1.4x	Miniature goals; Restart the game as quickly as possible; no offside rule.	1	3	18 min	5 min	-
[85]	4vs.4	10 × 15 m	19 m ²	20 × 25 m	62.5 m ²	3.3x	Restart the game as quickly as possible; verbal encouragement; free touches.	1	4	16 min	2 min	Passive
[61]	5vs.5 + GK	30 × 20 m	60 m ²	50 × 40 m	200 m ²	3.3x	Tournament scenario; restart the game as quickly as possible; verbal encouragement.	1	4	16 min	3 min	-
[86]	5vs.5 + GK 5vs.5	28 × 20 m	56 m ²	42 × 30 m	126 m ²	2.3x	Balls were disposed around the game areas.	1	3	12 min	3 min	Active
[87]	5vs.5 + GK	32 × 23 m	73.6 m ²	62 × 44 m	272.8 m ²	3.7x	Goalkeepers restart the game as quickly as possible.	1	3	24 min	5 min	Passive
[88]	5vs.5 + GK	32 × 23 m	73.6 m ²	62 × 44 m	272.8 m ²	3.7x	Goalkeepers restart the game as quickly as possible.	1	3	24 min	5 min	Passive
[39]	8vs.8 + GK	68 × 47 m	199.75 m ²	75 × 47 m	220.31 m ²	1.1x	Balls were disposed around the game areas; verbal encouragement.	1	1	30 min	-	-
[17]	5vs.5 + GK	30 × 20 m	60 m ²	50 × 40 m	200 m ²	3.3x	Balls were disposed around the game areas; verbal encouragement.	1	4	16 min	2 min	Active
[89]	3vs.3 + 4 4vs.4 + 4	20 × 15 m 20 × 20 m	50 m ² 50 m ²	30 × 20 m 32 × 25 m	100 m ² 100 m ²	2.0x	Balls were disposed around the game areas; verbal encouragement.	1 1	4 4	12 min 16 min	2 min 2 min	Passive
[19]	3vs.3 + GK + 1	36 × 27 m	138.9 m ²	40 × 29	165.7 m ²	1.2x	Offside rule; balls were disposed around the game areas; verbal encouragement; not technical and tactical instructions.	1	4	16 min	4 min	Passive
[90]	4vs.4	20 × 20 m	50 m ²	28.3 × 28.3 m	100 m ²	2x	Balls were disposed around the game areas; verbal encouragement.	1	3	4 min	10 min	Active
[91]	4vs.4	20 × 20 m	50 m ²	28.3 × 28.3 m	100 m ²	2x	Balls were disposed around the game areas; verbal encouragement.	1	3	4 min	10 min	Active
[92]	5vs.5	30 × 20 m	60 m ²	51 × 34 m	173.4 m ²	2.9x	Stop the ball with their foot backside to the limits of the pitch to score; balls were disposed around the game areas.	1	4	16 min	1 min	Passive

TABLE 4. Continue.

Study	SSG formats	Smaller pitch (length × width)	Smaller pitch (area per player - m ²)	Larger pitch (length × width)	Larger pitch (area per player - m ²)	Larger/ Smaller (m ²)	Task conditions	Sets	Reps	Work duration	Between reps duration	Type of recovery
[62]	4vs.3 4vs.4 4vs.5	20 × 15 m	42.9 m ² 37.5 m ² 33.3 m ²	30 × 25 m	107.1 m ² 93.75 m ² 83.3 m ²	2.5x 2.5x 2.5x	Coach did not intervene; Balls were disposed around the game areas.	1	4	16 min	4 min	Active
[93]	4vs.4	20 × 15 m	37.5 m ²	30 × 25 m	93.75 m ²	2.5x	Coach did not intervene; Balls were disposed around the game areas.	1	4	16 min	4 min	Active
[66]	4vs.4 + GK	40 × 30 m	120 m ²	68 × 47 m	320 m ²	2.7x	Coach players similar to match; offside rule in large pitch; no offside rule in small pitch.	1	5	20 min	4 min	-
[94]	4vs.4 + GK	37 × 17 m	60 m ²	40 × 20 m	80 m ²	1.3x	No verbal encouragement; Balls were disposed around the game areas; one referee.	1	2	40 min	5 min	Passive
[95]	3vs.3 4vs.4 5vs.5 6vs.6	12 × 20 m 16 × 24 m 20 × 28 m 24 × 32 m	40 m ² 48 m ² 56 m ² 64 m ²	18 × 30 m 24 × 36 m 30 × 42 m 36 × 48 m	90 m ² 108 m ² 126 m ² 144 m ²	2.3x 2.3x 2.3x 2.3x	With and without coach encouragement.	1	3	12 min	3 min	Active
[96]	5vs.5 8vs.8	30 × 40 m	120 m ²	105 × 68 m	325 m ²	2.7x	Smaller goals or normal goals.	1	1	20 min	-	-
[20]	4vs.4 + GK	23.8 × 36.8 m	88 m ²	37.4 × 57.8 m	216 m ²	2.5x	Not allowed passing to the goalkeeper; coach did not intervene.	1	3	7 min	7 min	Active
[58]	4vs.4 + GK	36.8 × 23.8 m	87.6 m ²	57.8 × 37.4 m	216.2 m ²	2.5x	Not allowed passing to the goalkeeper.	1	3	7 min	7 min	Active
[97]	6vs.6	46.7 × 30.3 m	118 m ²	52.9 × 34.4 m	152 m ²	1.3x	Scoring zone; balls were disposed around the game areas; coach did not intervene.	1	3	18 min	4 min	Passive
[98]	5vs.5	28 × 14 m	39.2 m ²	52 × 26 m	135.2 m ²	3.4x	Small goals.	1	2	10 min	5 min	-
[69]	4vs.4 + GK	24 × 16 m	38.4 m ²	30 × 20 m	60 m ²	1.6x	No offside rule; GK had 2-touch play; outfield players had to avoid long-range shots.	1	1	8 min	8 min	-

Notes. GK: goalkeepers;

TABLE 5. Summary of the included studies and results of physiological responses in smaller and larger pitch sizes.

Study	Format	Age category	N	Variable	Smaller Mean $\pm$ SD	Larger Mean $\pm$ SD	Larger-Smaller (%)	Tendency of change	Included in the meta-analysis
[71]	5vs.5 + GK	Adults	10	HR	164.3 $\pm$ 11.9	167.0 $\pm$ 13.2	1.9	Increase in larger pitch size	Yes
[71]	7vs.7 + GK	Adults	10	HR	161.2 $\pm$ 12.9	163.5 $\pm$ 12.8	1.4	Increase in larger pitch size	Yes
[71]	5vs.5 + GK	Adults	10	RPE	12.4 $\pm$ 1.2	13.2 $\pm$ 1.9	6.5	Increase in larger pitch size	Yes
[71]	7vs.7 + GK	Adults	10	RPE	12.3 $\pm$ 0.9	12.8 $\pm$ 1.2	4.1	Increase in larger pitch size	Yes
[73]	6vs.6 + 1	Adults	9	HR	86.7 $\pm$ 7.7	89.1 $\pm$ 4.6	2.8	Increase in larger pitch size	Yes
[74]	5vs.5 + GK	Adults	20	HR	83.4 $\pm$ 5.1	86.5 $\pm$ 4.5	3.7	Increase in larger pitch size	Yes
[74]	5vs.5 + GK	Adults	20	RPE	3.8 $\pm$ 1.5	6.6 $\pm$ 1.2	84.8	Increase in larger pitch size	Yes
[18]	5vs.5 + GK	Youth ^f	10	HR	86.0 $\pm$ 5.8	88.9 $\pm$ 3.9	4.5	Increase in larger pitch size	Yes
[18]	5vs.5 + GK	Youth ^f	10	RPE	5.7 $\pm$ 1.0	6.7 $\pm$ 0.8	17.5	Increase in larger pitch size	Yes
[75]	1vs.1	Youth ^g	19	HR	157 $\pm$ 8	169 $\pm$ 6	7.6	Increase in larger pitch size	Yes
[75]	1vs.1	Youth ^g	19	RPE	5.1 $\pm$ 1.6	8 $\pm$ 1	56.9	Increase in larger pitch size	Yes
[77]	7vs.7 + GK	Youth ^c	24	HR	82 $\pm$ 3	88 $\pm$ 6	7.3	Increase in larger pitch size	Yes
[77]	7vs.7 + GK	Youth ^c	24	RPE	267.1 $\pm$ 47.5	299.9 $\pm$ 41.3	12.3	Increase in larger pitch size	Yes
[77]	9vs.9 + GK	Youth ^c	24	HR	83 $\pm$ 6	85 $\pm$ 6	2.4	Increase in larger pitch size	Yes
[77]	9vs.9 + GK	Youth ^c	24	RPE	233.4 $\pm$ 28.7	270.9 $\pm$ 25.8	16.1	Increase in larger pitch size	Yes
[77]	11vs.11 + GK	Youth ^c	24	HR	81 $\pm$ 4	88 $\pm$ 4	8.6	Increase in larger pitch size	Yes
[77]	11vs.11 + GK	Youth ^c	24	RPE	228.6 $\pm$ 49.3	306.1 $\pm$ 39.3	33.9	Increase in larger pitch size	Yes
[14]	7vs.7 + GK	Youth ^b	22	HR	85.3 $\pm$ 7.1	88.3 $\pm$ 3.3	3.5	Increase in larger pitch size	Yes
[14]	7vs.7 + GK	Youth ^b	22	RPE	283 $\pm$ 26	297 $\pm$ 25	4.9	Increase in larger pitch size	Yes
[14]	9vs.9 + GK	Youth ^b	22	HR	84.7 $\pm$ 2.9	83.3 $\pm$ 4.5	-1.7	Decrease in larger pitch size	Yes
[14]	9vs.9 + GK	Youth ^b	22	RPE	297 $\pm$ 35	310 $\pm$ 35	4.4	Increase in larger pitch size	Yes
[14]	11vs.11 + GK	Youth ^b	22	HR	80.0 $\pm$ 5.5	83.1 $\pm$ 5.0	3.9	Increase in larger pitch size	Yes
[14]	11vs.11 + GK	Youth ^b	22	RPE	257 $\pm$ 55	285 $\pm$ 41	10.9	Increase in larger pitch size	Yes
[14]	7vs.7 + GK	Youth ^c	22	HR	81.8 $\pm$ 10.5	87.4 $\pm$ 4.4	3.5	Increase in larger pitch size	Yes
[14]	7vs.7 + GK	Youth ^c	22	RPE	267 $\pm$ 47.5	300 $\pm$ 41	12.4	Increase in larger pitch size	Yes
[14]	9vs.9 + GK	Youth ^c	22	HR	82.6 $\pm$ 4.7	84.7 $\pm$ 2.6	2.54	Increase in larger pitch size	Yes
[14]	9vs.9 + GK	Youth ^c	22	RPE	297 $\pm$ 35	271 $\pm$ 26	-8.8	Decrease in larger pitch size	Yes

TABLE 5. Continue.

Study	Format	Age category	N	Variable	Smaller Mean $\pm$ SD	Larger Mean $\pm$ SD	Larger-Smaller (%)	Tendency of change	Included in the meta-analysis
[14]	11vs.11 + GK	Youth ^c	22	HR	80.8 $\pm$ 2.8	87.6 $\pm$ 3.1	8.4	Increase in larger pitch size	Yes
[14]	11vs.11 + GK	Youth ^c	22	RPE	257 $\pm$ 55	306 $\pm$ 39	19.1	Increase in larger pitch size	Yes
[79]	5vs.5 + GK	Youth ^e	10	HR	180 $\pm$ 8	180 $\pm$ 8	0.0	No differences	Yes
[82]	11vs.11 + GK	Adults	40	HR	84.7 $\pm$ 2.7	83.2 $\pm$ 2.6	-1.8	Decrease in larger pitch size	Yes
[82]	11vs.11 + GK	Adults	40	RPE	7.3 $\pm$ 0.6	7.4 $\pm$ 0.5	1.4	Increase in larger pitch size	Yes
[85]	4vs.4 (SB)	Youth ^d	16	HR	166.9 $\pm$ 3.1	174.9 $\pm$ 3.2	4.8	Increase in larger pitch size	Yes
[85]	4vs.4 (SB)	Youth ^d	16	RPE	6.3 $\pm$ 0.9	7.1 $\pm$ 0.9	12.7	Increase in larger pitch size	Yes
[85]	4vs.4 (SG)	Youth ^d	16	HR	163.9 $\pm$ 3.2	170.9 $\pm$ 2.7	4.3	Increase in larger pitch size	Yes
[85]	4vs.4 (SG)	Youth ^d	16	RPE	5.8 $\pm$ 0.9	6.8 $\pm$ 0.8	17.2	Increase in larger pitch size	Yes
[61]	5vs.5 + GK	Youth ⁱ	8	HR	164 $\pm$ 14	168 $\pm$ 17	2.4	Increase in larger pitch size	Yes
[86]	5vs.5 + GK	Youth ^h	29	HR	169.3 $\pm$ 6.2	176.4 $\pm$ 7.5	4.2	Increase in larger pitch size	Yes
[86]	5vs.5 + GK	Youth ^h	29	RPE	4.9 $\pm$ 1.3	7.5 $\pm$ 1.8	53.1	Increase in larger pitch size	Yes
[86]	5vs.5	Youth ^h	29	HR	174.2 $\pm$ 6.5	177.1 $\pm$ 5.8	1.7	Increase in larger pitch size	Yes
[86]	5vs.5	Youth ^h	29	RPE	4.7 $\pm$ 1.1	7.1 $\pm$ 1.1	51.1	Increase in larger pitch size	Yes
[17]	5vs.5 + GK	Youth ^h	8	HR	175 $\pm$ 9	169 $\pm$ 6	-3.4	Decrease in larger pitch size	Yes
[89]	3vs.3 + 4	Youth ^d	16	HR	176.3 $\pm$ 2.5	184.2 $\pm$ 6.5	4.5	Increase in larger pitch size	Yes
[89]	4vs.4 + 4	Youth ^d	16	HR	175.0 $\pm$ 7.7	183.5 $\pm$ 8.4	4.9	Increase in larger pitch size	Yes
[19]	3vs.3 + GK + 1	Youth ^c	24	HR	168.0 $\pm$ 10.7	166.3 $\pm$ 11.9	-1.0	Increase in smaller pitch size	Yes
[19]	3vs.3 + GK + 1	Youth ^d	24	HR	164.1 $\pm$ 12.5	168.9 $\pm$ 11.2	2.9	Increase in larger pitch size	Yes
[91]	4vs.4	Youth ⁱ	16	HR	169.4 $\pm$ 12.1	169.3 $\pm$ 11.6	-0.1	Decrease in larger pitch size	Yes
[91]	4vs.4	Youth ⁱ	16	HR	163.7 $\pm$ 10.9	164.4 $\pm$ 9.7	0.4	Increase in larger pitch size	Yes
[91]	4vs.4	Youth ⁱ	16	HR	160.1 $\pm$ 8.8	165.5 $\pm$ 8.7	3.4	Increase in larger pitch size	Yes
[92]	5vs.5	Youth ^c	10	HR	85 $\pm$ 4	85 $\pm$ 5	0.0	No differences	Yes
[62]	4vs.3	Youth ⁱ	20	RPE	4.0 $\pm$ 0.5	3.8 $\pm$ 1.1	-5.0	Decrease in larger pitch size	Yes
[62]	4vs.4	Youth ⁱ	20	RPE	4.3 $\pm$ 0.8	4.0 $\pm$ 1.1	-7.0	No differences	Yes
[62]	4vs.5	Youth ⁱ	20	RPE	4.5 $\pm$ 0.8	5.0 $\pm$ 1.1	11.1	Increase in larger pitch size	Yes
[62]	4vs.2 + 1	Youth ⁱ	20	RPE	4.5 $\pm$ 0.8	5.3 $\pm$ 0.8	17.8	Increase in larger pitch size	Yes
[62]	4vs.2 + 2	Youth ⁱ	20	RPE	3.8 $\pm$ 0.8	5.3 $\pm$ 1.3	39.5	Increase in larger pitch size	Yes
[62]	4vs.2 + 3	Youth ⁱ	20	RPE	3.5 $\pm$ 1.1	3.3 $\pm$ 1.3	-5.7	No differences	Yes

TABLE 5. Continue.

Study	Format	Age category	N	Variable	Smaller Mean $\pm$ SD	Larger Mean $\pm$ SD	Larger-Smaller (%)	Tendency of change	Included in the meta-analysis
[93]	4vs.4	Youth ^a	16	RPE	3.9 $\pm$ 1.1	3.5 $\pm$ 1.0	-11.4	Decrease in larger pitch size	Yes
[93]	4vs.4	Youth ^e	18	RPE	4.3 $\pm$ 1.1	4.6 $\pm$ 1.0	7.0	Increase in larger pitch size	Yes
[93]	4vs.4	Youth ⁱ	18	RPE	4.7 $\pm$ 0.9	4.9 $\pm$ 0.9	4.3	Increase in larger pitch size	Yes
[94]	4vs.4 + GK	Youth ⁱ	10	HR	160 $\pm$ 10	167 $\pm$ 9	4.4	Increase in larger pitch size	Yes
[95]	3vs.3	Adults	20	HR	89.5 $\pm$ 2.9	90.9 $\pm$ 2.0	1.4	Increase in larger pitch size	Yes
[95]	4vs.4	Adults	20	HR	88.7 $\pm$ 2.0	89.7 $\pm$ 1.8	1.0	Increase in larger pitch size	Yes
[95]	5vs.5	Adults	20	HR	87.8 $\pm$ 3.6	88.8 $\pm$ 2.3	1.0	Increase in larger pitch size	Yes
[95]	6vs.6	Adults	20	HR	86.4 $\pm$ 2.0	86.9 $\pm$ 2.4	0.5	Increase in larger pitch size	Yes
[95]	3vs.3	Adults	20	RPE	8.1 $\pm$ 0.6	8.5 $\pm$ 0.4	4.9	Increase in larger pitch size	Yes
[95]	4vs.4	Adults	20	RPE	7.6 $\pm$ 0.5	8.1 $\pm$ 0.5	6.6	Increase in larger pitch size	Yes
[95]	5vs.5	Adults	20	RPE	7.2 $\pm$ 0.9	7.5 $\pm$ 0.6	4.2	Increase in larger pitch size	Yes
[95]	6vs.6	Adults	20	RPE	6.8 $\pm$ 0.6	7.2 $\pm$ 0.8	5.9	Increase in larger pitch size	Yes
[95]	3vs.3	Adults	20	HR	87.6 $\pm$ 1.7	89.1 $\pm$ 1.8	1.5	Increase in larger pitch size	Yes
[95]	4vs.4	Adults	20	HR	86.5 $\pm$ 3.4	87.2 $\pm$ 2.8	0.7	Increase in larger pitch size	Yes
[95]	5vs.5	Adults	20	HR	86.0 $\pm$ 4.0	86.9 $\pm$ 3.2	0.9	Increase in larger pitch size	Yes
[95]	6vs.6	Adults	20	HR	83.8 $\pm$ 5.0	85.0 $\pm$ 3.6	1.2	Increase in larger pitch size	Yes
[95]	3vs.3	Adults	20	RPE	6.6 $\pm$ 0.4	7.2 $\pm$ 0.7	0.6	Increase in larger pitch size	Yes
[95]	4vs.4	Adults	20	RPE	6.3 $\pm$ 0.5	6.8 $\pm$ 0.5	0.5	Increase in larger pitch size	Yes
[95]	5vs.5	Adults	20	RPE	5.9 $\pm$ 0.7	6.2 $\pm$ 0.6	0.3	Increase in larger pitch size	Yes
[95]	6vs.6	Adults	20	RPE	4.8 $\pm$ 0.9	5.9 $\pm$ 0.5	1.1	Increase in larger pitch size	Yes
[96]	5vs.5 8vs.8	Youth ^a	45	HR	174 $\pm$ 10	168 $\pm$ 12	-3.4	Decrease in larger pitch size	Yes
[96]	8vs.8 11vs.11	Youth ^c	41	HR	170 $\pm$ 10	171 $\pm$ 12	0.6	Increase in larger pitch size	Yes

SD: standard-deviation; HR: heart rate; RPE: rate of perceived exertion; SB: stop-ball; SG: small-goals; NR: data not reported; %: percentage of difference; a: Under-11 or below group; b: Under-12; group; c: Under-13 group; d: Under-14 group; e; under-15 group; f: under-16 group; g: under-17 group; h: under-18 group; i: under-23 group.

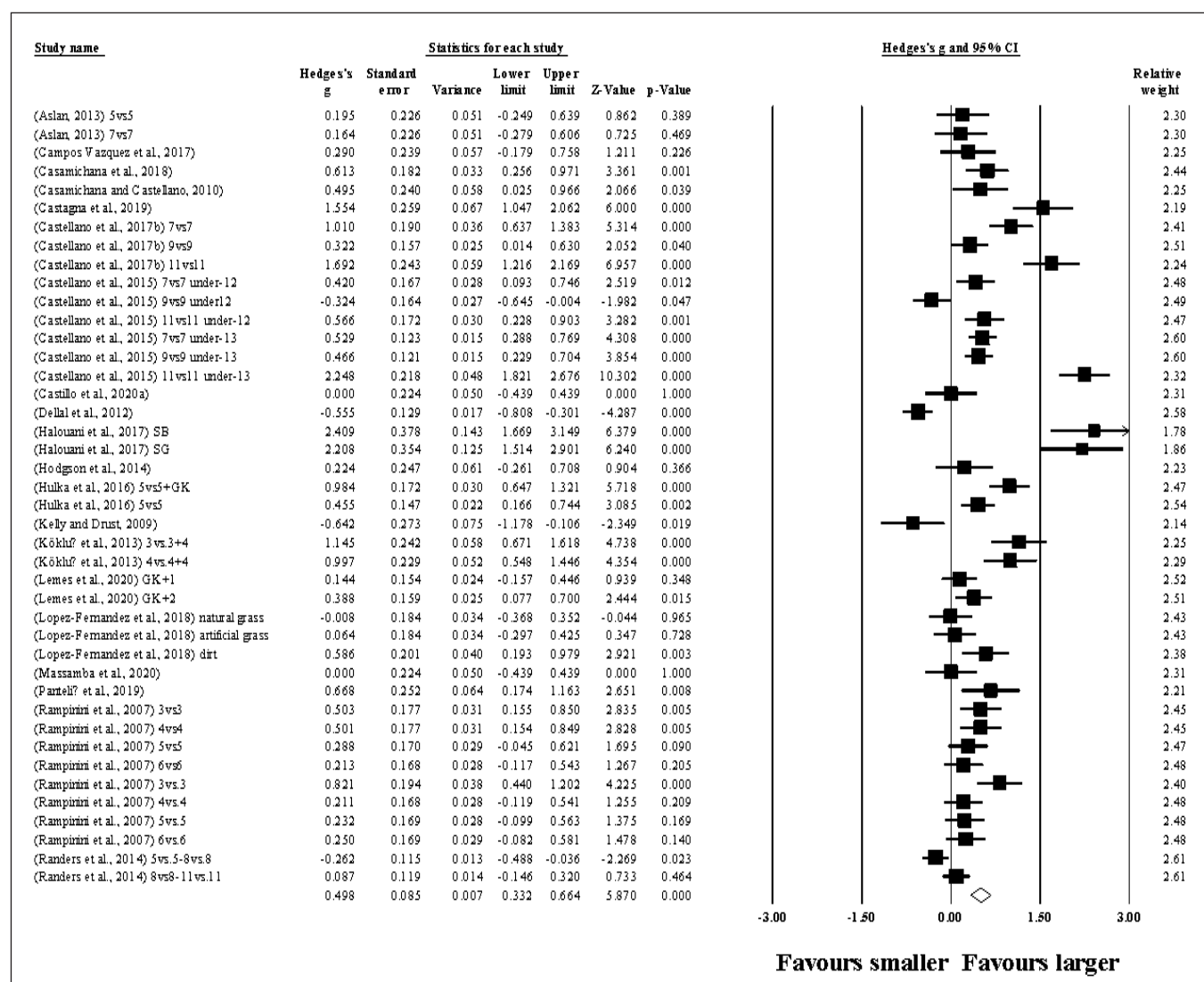


FIG. 2. Forest plot of changes in heart rate, in soccer players participating in small-sided games using smaller compared to larger pitch sizes. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical relative weight of the study. The white diamond reflects the overall result.

Forty-two study groups provided data for HR, involving 42 small- and 42 larger pitch sizes being compared (pooled $n = 898$). Results (Figure 2) showed that SSGs played at larger pitches induced greater HR compared to smaller pitches ($ES = 0.50$, small; 95% $CI = 0.33$ to 0.66 ; $p < 0.001$; $I^2 = 89.1\%$; Egger's test $p < 0.001$, with a corrected value of $ES = 0.67$, 95% $CI = 0.48$ to 0.86 ; supplementary Figure 1).

Thirty-six study groups provided data for RPE, involving 32 small- and 32 larger pitch sizes being compared (pooled $n = 735$). Results (Figure 3) showed that SSGs played at larger pitches induced greater RPE compared to smaller pitches ($ES = 0.70$, moderate; 95% $CI = 0.52$ to 0.89 ; $p < 0.001$; $I^2 = 88.6\%$; Egger's test $p < 0.001$, with a corrected value equal to the observed value; supplementary Figure 2).

Moderator analyses for HR and RPE

The HR was greater at larger compared to smaller pitches when SSGs were played with either small (14 study groups; $ES = 0.55$; $p < 0.001$; $I^2 = 84.9\%$), medium (19 study groups; $ES = 0.30$; $p = 0.001$; $I^2 = 79.2\%$) and large (8 study groups; $ES = 0.69$; $p = 0.048$; $I^2 = 96.1\%$) formats, although without significant sub-group difference between formats ($p = 0.056$).

The HR was greater at larger compared to smaller pitches when SSGs were played by young/youth (29 study groups; $ES = 0.60$; $p < 0.001$; $I^2 = 90.9\%$) and adult players (13 study groups; $ES = 0.28$; $p = 0.009$; $I^2 = 78.4\%$), with significant sub-group difference according to the age of the soccer players ($p = 0.037$).

The RPE was greater at larger compared to smaller pitches when SSGs were played with either small (13 study groups; $ES = 0.48$;

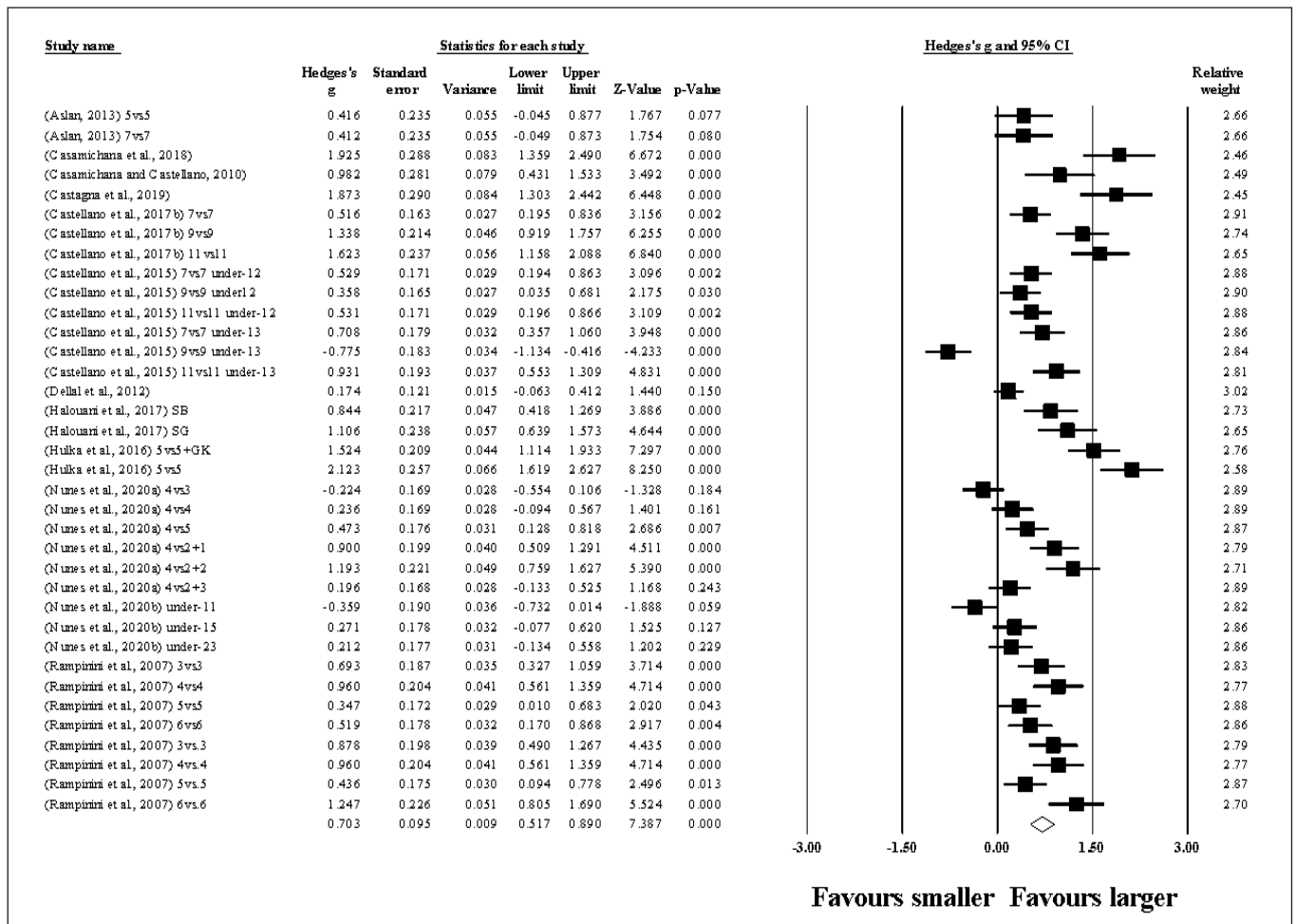


FIG. 3. Forest plot of changes in rating of perceived exertion, in soccer players participating in small-sided games using smaller compared to larger pitch sizes. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical relative weight of the study. The white diamond reflects the overall result.

$p < 0.001$; $I^2 = 84.2\%$), medium (15 study groups; $ES = 0.89$; $p < 0.001$; $I^2 = 83.5\%$) and large (7 study groups; $ES = 0.59$; $p = 0.03$; $I^2 = 93.9\%$) formats, although without significant sub-group difference between formats ($p = 0.088$).

The RPE was greater at larger compared to smaller pitches when SSGs were played by young/youth (24 study groups; $ES = 0.69$; $p < 0.001$; $I^2 = 90.9\%$) and adult players (12 study groups; $ES = 0.72$; $p < 0.001$; $I^2 = 79.9\%$), without significant sub-group difference according to the age of the soccer players ($p = 0.895$).

Smaller vs. larger pitch sizes during SSG: effects on physical demands

A summary of the included studies and results of physical demands (TD, HSR, ACC and DEC) reported in smaller and larger SSGs are provided in Table 6.

Thirty-six study groups provided data for TD, involving 36 smaller and 36 larger pitch sizes being compared (pooled $n = 1.035$).

Results (Figure 4) showed that SSGs played at larger pitches induced greater TD compared to smaller pitches ($ES = 1.95$, large; 95% CI = 1.62 to 2.29; $p < 0.001$; $I^2 = 95.9\%$; Egger's test $p < 0.001$, with a corrected value of $ES = 2.49$, 95% CI = 1.89 to 3.10; supplementary Figure 3).

Thirty-five study groups provided data for HSR, involving 35 smaller and 35 larger pitch sizes being compared (pooled $n = 920$). Results (Figure 5) showed that SSGs played at larger pitches induced greater HSR compared to smaller pitches ($ES = 1.20$, moderate; 95% CI = 0.93 to 1.47; $p < 0.001$; $I^2 = 94.4\%$; Egger's test $p < 0.001$, with a corrected value of $ES = 1.32$, 95% CI = 0.95 to 1.70; supplementary Figure 4).

Six study groups provided data for ACC, involving 6 smaller and 6 larger pitch sizes being compared (pooled $n = 86$). Results (Figure 6) showed that SSGs played at larger pitches induced similar ACC compared to smaller pitches ($ES = 0.45$, small; 95% CI = -0.29 to 1.18; $p = 0.232$; $I^2 = 93.5\%$; Egger's test $p = 0.040$,

TABLE 6. Summary of the included studies and results of physical demands in smaller and larger pitch sizes.

Study	Format	Age category	N	Variable	Smaller Mean $\pm$ SD	Larger Mean $\pm$ SD	Larger-Smaller (%)	Tendency of change	Included in the meta-analysis
[72]	4vs.4	Youth ^g	16	TD	1000 $\pm$ 131	1095 $\pm$ 89	9.5	Increase in larger pitch size	Yes
[72]	4vs.4	Youth ^g	16	HSR	19.3 $\pm$ 14.9	64.9 $\pm$ 24.8	45.6	Increase in larger pitch size	Yes
[72]	4vs.4	Youth ^g	16	ACC	12.2 $\pm$ 5.5	10.5 $\pm$ 3.8	-13.9	Decrease in larger pitch size	Yes
[73]	6vs.6 + 1	Adults	9	TD	93.8 $\pm$ 11.6	103.4 $\pm$ 11.2	10.2	Increase in larger pitch size	Yes
[73]	6vs.6 + 1	Adults	9	HSR	46.9 $\pm$ 22.1	492.2 $\pm$ 181.3	949	Increase in larger pitch size	Yes
[74]	5vs.5 + GK	Adults	20	TD	101.2 $\pm$ 11.8	131.4 $\pm$ 14.4	29.8	Increase in larger pitch size	Yes
[74]	5vs.5 + GK	Adults	20	ACC	3.8 $\pm$ 3.3	2.3 $\pm$ 2.4	-39.5	Decrease in larger pitch size	Yes
[74]	5vs.5 + GK	Adults	20	DEC	4.5 $\pm$ 4.1	1.8 $\pm$ 2.0	-60	Decrease in larger pitch size	Yes
[18]	5vs.5 + GK	Youth ^f	10	TD	87.0 $\pm$ 4.6	125.0 $\pm$ 6.2	43.7	Increase in larger pitch size	Yes
[18]	5vs.5 + GK	Youth ^f	10	HSR	4.9 $\pm$ 5.5	74.2 $\pm$ 58.9	1414.3	Increase in larger pitch size	Yes
[75]	1vs.1	Youth ^g	19	TD	378 $\pm$ 46	601 $\pm$ 54	58.9	Increase in larger pitch size	Yes
[75]	1vs.1	Youth ^g	19	HSR	15 $\pm$ 9	146 $\pm$ 25	873.3	Increase in larger pitch size	Yes
[75]	1vs.1	Youth ^g	19	ACC	82 $\pm$ 16	145 $\pm$ 14	76.8	Increase in larger pitch size	Yes
[75]	1vs.1	Youth ^g	19	DEC	34 $\pm$ 6	69 $\pm$ 6	102.9	Increase in larger pitch size	Yes
[76]	7vs.7 + GK	Youth ^c	14	TD	663.9 $\pm$ 76.6	819.7 $\pm$ 106.5	23.5	Increase in larger pitch size	Yes
[76]	7vs.7 + GK	Youth ^c	14	HSR	7.7 $\pm$ 8.4	38.1 $\pm$ 38.2	394.8	Increase in larger pitch size	Yes
[76]	7vs.7 + GK	Youth ^d	14	TD	670.9 $\pm$ 67.9	871.0 $\pm$ 81.9	29.8	Increase in larger pitch size	Yes
[76]	7vs.7 + GK	Youth ^d	14	HSR	6.5 $\pm$ 8.1	59.9 $\pm$ 43.5	821.5	Increase in larger pitch size	Yes
[77]	7vs.7 + GK	Youth ^d	24	TD	1816 $\pm$ 155	2307 $\pm$ 212	27.1	Increase in larger pitch size	Yes
[77]	7vs.7 + GK	Youth ^d	24	HSR	48 $\pm$ 31	202 $\pm$ 78	320.8	Increase in larger pitch size	Yes
[77]	9vs.9 + GK	Youth ^d	24	TD	1845 $\pm$ 141	2250 $\pm$ 107	21.9	Increase in larger pitch size	Yes
[77]	9vs.9 + GK	Youth ^d	24	HSR	70 $\pm$ 32	164 $\pm$ 41	134.3	Increase in larger pitch size	Yes
[77]	11vs.11 + GK	Youth ^d	24	TD	1766 $\pm$ 181	2314 $\pm$ 134	31.1	Increase in larger pitch size	Yes
[77]	11vs.11 + GK	Youth ^d	24	HSR	62 $\pm$ 43	200 $\pm$ 105	222.6	Increase in larger pitch size	Yes
[14]	7vs.7 + GK	Youth ^b	22	TD	1718 $\pm$ 150	2186 $\pm$ 90	27.2	Increase in larger pitch size	Yes
[14]	7vs.7 + GK	Youth ^b	22	HSR	72 $\pm$	199 $\pm$	176.4	Increase in larger pitch size	No Reason: SD not reported
[14]	9vs.9 + GK	Youth ^b	22	TD	1867 $\pm$ 126	2159 $\pm$ 183	15.6	Increase in larger pitch size	Yes
[14]	9vs.9 + GK	Youth ^b	22	HSR	89 $\pm$	197 $\pm$	121.3	Increase in larger pitch size	No Reason: no reported SD

TABLE 6. Continue.

Study	Format	Age category	N	Variable	Smaller Mean $\pm$ SD	Larger Mean $\pm$ SD	Larger-Smaller (%)	Tendency of change	Included in the meta-analysis
[14]	11vs.11 + GK	Youth ^b	22	TD	1844 $\pm$ 254	2168 $\pm$ 127	17.6	Increase in larger pitch size	Yes
[14]	11vs.11 + GK	Youth ^b	22	HSR	109 $\pm$	236 $\pm$	116.5	Increase in larger pitch size	No Reason: no reported SD
[14]	7vs.7 + GK	Youth ^c	22	TD	1816 $\pm$ 155	2307 $\pm$ 212	34.3	Increase in larger pitch size	Yes
[14]	7vs.7 + GK	Youth ^c	22	HSR	55 $\pm$ NR	218 $\pm$ NR	296.4	Increase in larger pitch size	No Reason: SD not reported
[14]	9vs.9 + GK	Youth ^c	22	TD	1845 $\pm$ 141	2250 $\pm$ 107	20.5	Increase in larger pitch size	Yes
[14]	9vs.9 + GK	Youth ^c	22	HSR	91 $\pm$ NR	181 $\pm$ NR	98.9	Increase in larger pitch size	No Reason: no reported SD
[14]	11vs.11 + GK	Youth ^c	22	TD	1766 $\pm$ 181	2314 $\pm$ 134	25.5	Increase in larger pitch size	Yes
[14]	11vs.11 + GK	Youth ^c	22	HSR	72 $\pm$ NR	218 $\pm$ NR	202.8	Increase in larger pitch size	No Reason: no reported SD
[78]	6vs.6	Youth ^b	24	TD	466.1 $\pm$ 61.1	579.0 $\pm$ 90.1	24.2	Increase in larger pitch size	Yes
[78]	6vs.6	Youth ^b	24	HSR	3.4 $\pm$ 5.3	31.2 $\pm$ 26.1	817.6	Increase in larger pitch size	Yes
[79]	5vs.5 + GK	Youth ^e	10	TD	2254 $\pm$ 241	2603 $\pm$ 261	15.5	Increase in larger pitch size	Yes
[79]	5vs.5 + GK	Youth ^e	19	HSR	4 $\pm$ 9	23 $\pm$ 26	475	Increase in larger pitch size	Yes
[80]	5vs.5 + GK	Youth ^e	20	TD	2223 $\pm$ 248	2629 $\pm$ 227	18.3	Increase in larger pitch size	Yes
[80]	5vs.5 + GK	Youth ^e	20	HSR	3 $\pm$ 4	28 $\pm$ 21	984.3	Increase in larger pitch size	Yes
[80]	5vs.5 + GK	Youth ^e	20	ACC	409 $\pm$ 47	403 $\pm$ 57	-1.6	Decrease in larger pitch size	Yes
[80]	5vs.5 + GK	Youth ^e	20	DEC	353 $\pm$ 52	361 $\pm$ 53	2.3	Increase in larger pitch size	Yes
[68]	11vs.11 + GK	Adults	10	TD	2511.2 $\pm$ 279.73	136.6 $\pm$ 323.8	24.9	Increase in larger pitch size	Yes
[68]	11vs.11 + GK	Adults	10	HSR	93.6 $\pm$ 43.5	256.2 $\pm$ 76.2	173.7	Increase in larger pitch size	Yes
[82]	11vs.11 + GK	Adults	40	TD	2664 $\pm$ 237	11173 $\pm$ 524	319.4	Increase in larger pitch size	Yes
[82]	11vs.11 + GK	Adults	40	HSR	353 $\pm$ 59.1	483 $\pm$ 71.2	36.8	Increase in larger pitch size	Yes
[83]	5vs.5 + GK	Youth ^g	11	TD	3067 $\pm$ 383	4068 $\pm$ 332	32.6	Increase in larger pitch size	Yes
[83]	5vs.5 + GK	Youth ^g	11	HSR	98 $\pm$ 47	538 $\pm$ 157	448.9	Increase in larger pitch size	Yes
[61]	5vs.5 + GK	Youth ⁱ	8	TD	1532 $\pm$ 145	1934 $\pm$ 133	26.2	Increase in larger pitch size	Yes
[61]	5vs.5 + GK	Youth ⁱ	8	HSR	0 $\pm$ 0	61 $\pm$ 47	6100	Increase in larger pitch size	Yes
[61]	5vs.5 + GK	Youth ⁱ	8	ACC	230 $\pm$ 111	327 $\pm$ 70	42.2	Increase in larger pitch size	Yes
[61]	5vs.5 + GK	Youth ⁱ	8	DEC	198 $\pm$ 89	298 $\pm$ 68	50.5	Increase in larger pitch size	Yes

TABLE 6. Continue.

Study	Format	Age category	N	Variable	Smaller Mean $\pm$ SD	Larger Mean $\pm$ SD	Larger-Smaller (%)	Tendency of change	Included in the meta-analysis
[86]	5vs.5 + GK	Youth ^h	29	TD	372.4 $\pm$ 13.8	496.8 $\pm$ 26.1	33.4	Increase in larger pitch size	Yes
[86]	5vs.5	Youth ^h	29	TD	355.6 $\pm$ 17.0	488.7 $\pm$ 26.7	37.4	Increase in larger pitch size	Yes
[88]	5vs.5 + GK	Adults	3	TD	445.1 $\pm$ 44.3	255.2 $\pm$ 25.9	-42.7	Decrease in larger pitch size	Yes
[88]	5vs.5 + GK	Adults	3	HSR	0	1.6 $\pm$ 2.1	-	Increase in larger pitch size	Yes
[88]	5vs.5 + GK	Adults	3	ACC	5.5 $\pm$ 3.9	2.7 $\pm$ 1.9	-50.9	Decrease in larger pitch size	Yes
[88]	5vs.5 + GK	Adults	3	DEC	4.2 $\pm$ 2.9	2.5 $\pm$ 1.6	-40.5	Decrease in larger pitch size	Yes
[39]	8vs.8 + GK	Youth ^b	149	TD	2420.9 $\pm$ 215.7	2494.9 $\pm$ 203.3	3.1	Increase in larger pitch size	Yes
[39]	8vs.8 + GK	Youth ^b	149	HSR	1108.8 $\pm$ 492.8	924.0 $\pm$ 369.6	-16.7	Decrease in larger pitch size	Yes
[19]	3vs.3 + GK + 1	Youth ^c	48	TD	447.7 $\pm$ 45.3	457.8 $\pm$ 49.9	2.3	Increase in larger pitch size	Yes
[19]	3vs.3 + GK + 1	Youth ^d	48	HSR	13.5 $\pm$ 0.4	15.0 $\pm$ 0.5	11.1	Increase in larger pitch size	Yes
[90]	4vs.4	Youth ⁱ	16	TD	399.0 $\pm$ 33.4	458.6 $\pm$ 52.0	14.9	Increase in larger pitch size	Yes
[90]	4vs.4	Youth ⁱ	16	HSR	21.0 $\pm$ 11.3	55.1 $\pm$ 31.3	162.4	Increase in larger pitch size	Yes
[62]	4vs.3	Youth ⁱ	20	HSR	1.0 $\pm$ 1.1	5.8 $\pm$ 5.1	480	Increase in larger pitch size	Yes
[62]	4vs.4	Youth ⁱ	20	HSR	2.0 $\pm$ 2.1	9.3 $\pm$ 8.3	365	Increase in larger pitch size	Yes
[62]	4vs.5	Youth ⁱ	20	HSR	1.5 $\pm$ 1.3	10.8 $\pm$ 6.7	620	No differences	Yes
[62]	4vs.2 + 1	Youth ⁱ	20	HSR	2.3 $\pm$ 3.8	10.0 $\pm$ 6.7	335	Increase in larger pitch size	Yes
[62]	4vs.2 + 2	Youth ⁱ	20	HSR	1.5 $\pm$ 6	7.8 $\pm$ 5.9	420	Increase in larger pitch size	Yes
[62]	4vs.2 + 3	Youth ⁱ	20	HSR	3.5 $\pm$	7.3 $\pm$ 4.3	109	Increase in larger pitch size	Yes
[93]	4vs.4	Youth ^a	16	HSR	5.9 $\pm$ 6.0	30.9 $\pm$ 25.7	423.7	Increase in larger pitch size	Yes
[93]	4vs.4	Youth ^e	18	HSR	3.9 $\pm$ 6.7	9.2 $\pm$ 10.4	135.9	Increase in larger pitch size	Yes
[93]	4vs.4	Youth ⁱ	18	HSR	3.4 $\pm$ 4.3	5.7 $\pm$ 5.7	67.6	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ^c	36	TD	111.5 $\pm$ 10.9	128.7 $\pm$ 12.0	15.4	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ^c	36	HSR	4.6 $\pm$ 7.0	24.2 $\pm$ 20.4	426.1	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ^e	43	TD	121.3 $\pm$ 11.5	132.9 $\pm$ 13.8	9.6	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ^e	43	HSR	11.2 $\pm$ 11.7	43.8 $\pm$ 30.7	291.1	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ^g	28	TD	124.3 $\pm$ 9.6	134.4 $\pm$ 11.8	8.1	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ^g	28	HSR	12.8 $\pm$ 11.8	49.7 $\pm$ 28.6	288.3	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ⁱ	43	TD	128.3 $\pm$ 11.0	140.7 $\pm$ 12.0	9.7	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ⁱ	43	HSR	17.3 $\pm$ 14.4	50.3 $\pm$ 27.4	190.8	Increase in larger pitch size	Yes

TABLE 6. Continue.

Study	Format	Age category	N	Variable	Smaller Mean $\pm$ SD	Larger Mean $\pm$ SD	Larger-Smaller (%)	Tendency of change	Included in the meta-analysis
[94]	4vs.4 + GK	Youth ⁱ	10	TD	3444 $\pm$ 293	3517 $\pm$ 152	2.1	Increase in larger pitch size	Yes
[94]	4vs.4 + GK	Youth ⁱ	10	HSR	31 $\pm$ 15	87 $\pm$ 51	180.6	Increase in larger pitch size	Yes
[96]	5vs.5 8vs.8	Youth ^a	86	TD	1754 $\pm$ 237	1771 $\pm$ 314	1.0	Increase in larger pitch size	Yes
[96]	5vs.5 8vs.8	Youth ^a	86	HSR	2 $\pm$ 6	6 $\pm$ 10	200.0	Increase in larger pitch size	Yes
[96]	8vs.8 11vs.11	Youth ^c	86	TD	1821 $\pm$ 325	2038 $\pm$ 328	11.9	Increase in larger pitch size	Yes
[96]	8vs.8 11vs.11	Youth ^c	86	HSR	2.5 $\pm$ NR	7.6 $\pm$ NR	204.0	Increase in larger pitch size	No Reason: no reported SD

SD: standard-deviation; TD: total distance; HSR: high speed running; ACC: accelerations; DEC: decelerations; %: percentage of difference; a: Under-11 group or below; b: Under-12; group; c: Under-13 group; d: Under-14 group; e: under-15 group; f: under-16 group; g: under-17 group; h: under-18 group; i: under-23 group; NR: non-reported

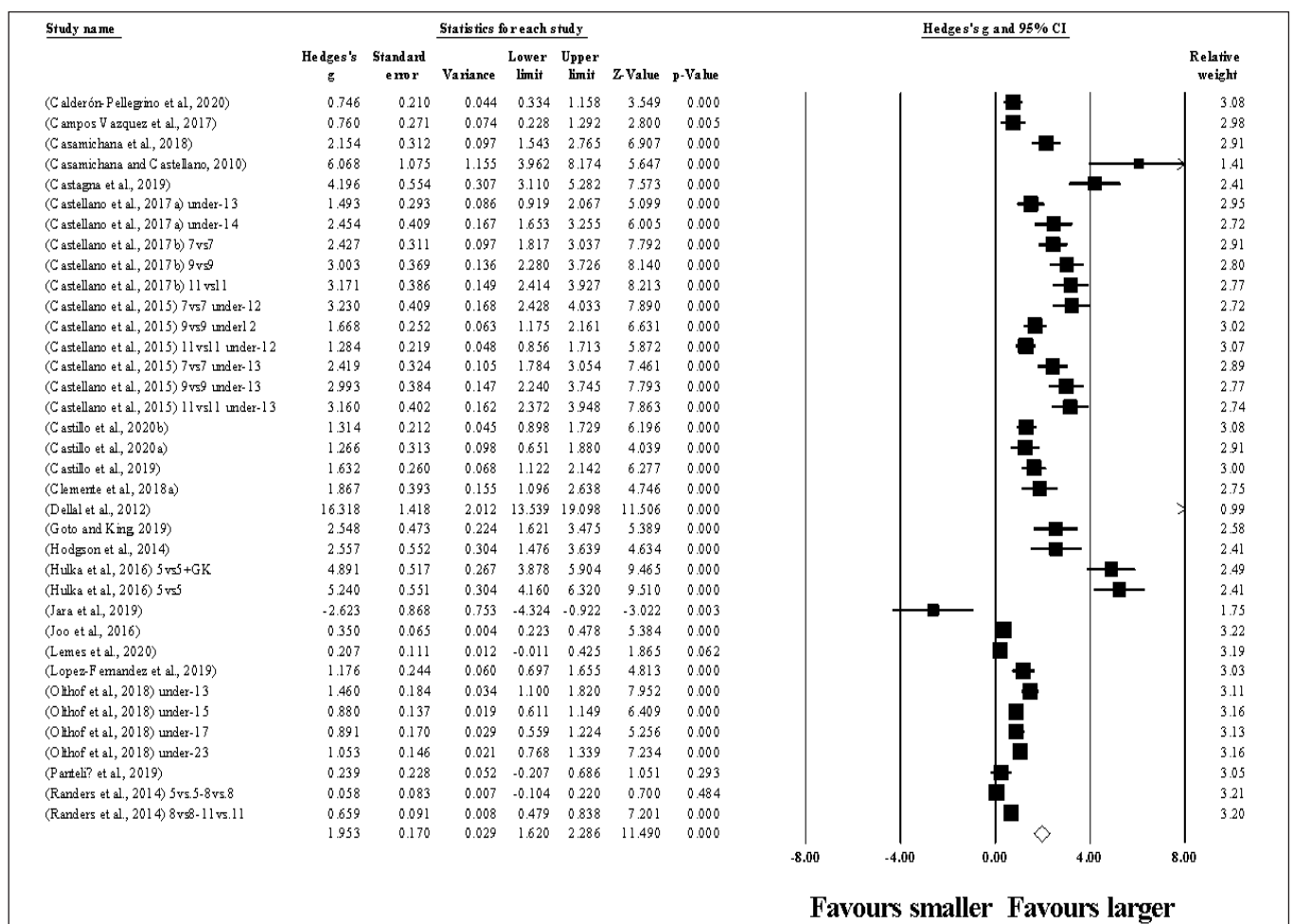


FIG. 4. Forest plot of changes in total distance, in soccer players participating in small-sided games using smaller compared to larger pitch sizes. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical relative weight of the study. The white diamond reflects the overall result.

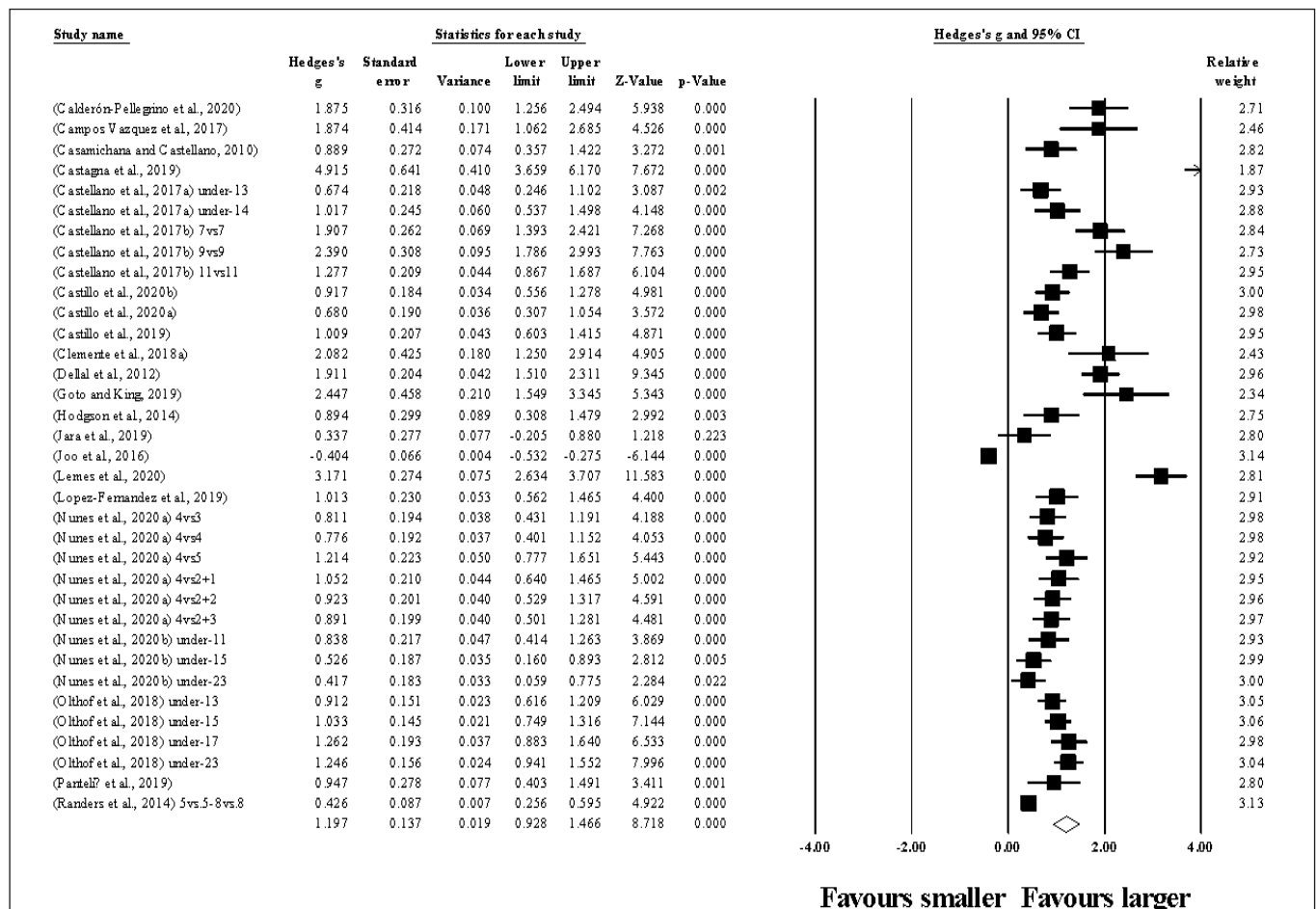


FIG. 5. Forest plot of changes in high speed running distance, in soccer players participating in small-sided games using smaller compared to larger pitch sizes. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical relative weight of the study. The white diamond reflects the overall result.

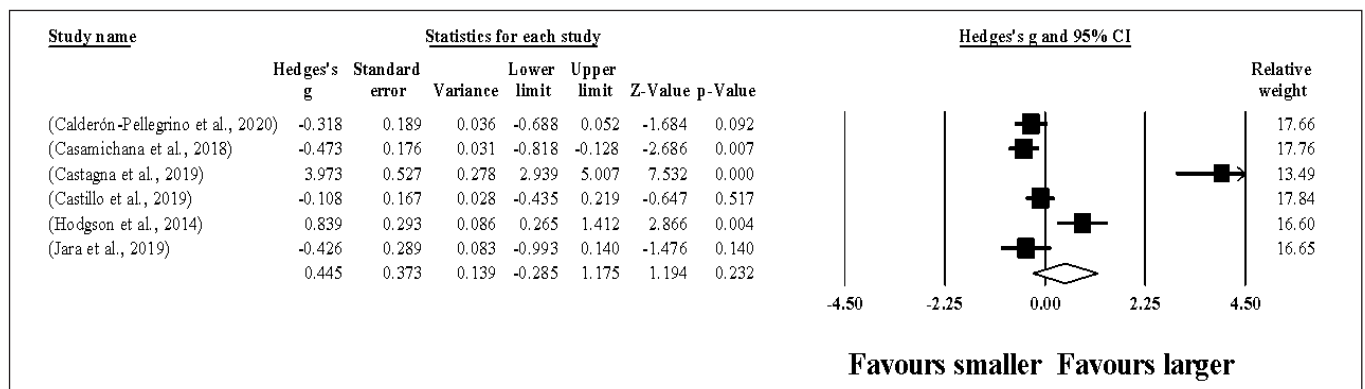


FIG. 6. Forest plot of changes in acceleration actions, in soccer players participating in small-sided games using smaller compared to larger pitch sizes. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical relative weight of the study. The white diamond reflects the overall result.

with a corrected value of $ES = 0.69$, 95% $CI = -0.17$ to 1.55 ; supplementary Figure 5).

Five study groups provided data for DEC, involving 5 smaller and 5 larger pitch sizes being compared (pooled $n = 70$). Results (Figure 7) showed that SSGs played at larger pitches induced similar DEC compared to smaller pitches ($ES = 0.85$, moderate; 95% $CI = -0.20$ to 1.90 ; $p = 0.111$; $I^2 = 95.3\%$; Egger's test $p = 0.049$, with a corrected value of $ES = 1.40$, 95% $CI = -0.17$ to 2.97 ; supplementary Figure 6).

Moderator analyses for TD, and HSR

The TD was greater at larger compared to smaller pitches when SSGs were played with either small (8 study groups; $ES = 0.83$; $p < 0.001$;

$I^2 = 86.7\%$), medium (18 study groups; $ES = 2.04$; $p < 0.001$; $I^2 = 96.3\%$) and large (9 study groups; $ES = 3.11$; $p < 0.001$; $I^2 = 96.8\%$) formats, with significant sub-group difference between formats ($p < 0.001$).

The TD was greater at larger compared to smaller pitches when SSGs were played by young/youth (31 study groups; $ES = 1.90$; $p < 0.001$; $I^2 = 95.6\%$) and adult players (5 study groups; $ES = 3.21$; $p = 0.007$; $I^2 = 97.2\%$), without significant sub-group difference according to the age of the soccer players ($p = 0.272$).

The HSR was greater at larger compared to smaller pitches when SSGs were played with either small (17 study groups; $ES = 1.09$; $p < 0.001$; $I^2 = 83.4\%$), medium (13 study groups; $ES = 0.93$; $p < 0.001$; $I^2 = 94.9\%$) and large (4 study groups; $ES = 1.87$;

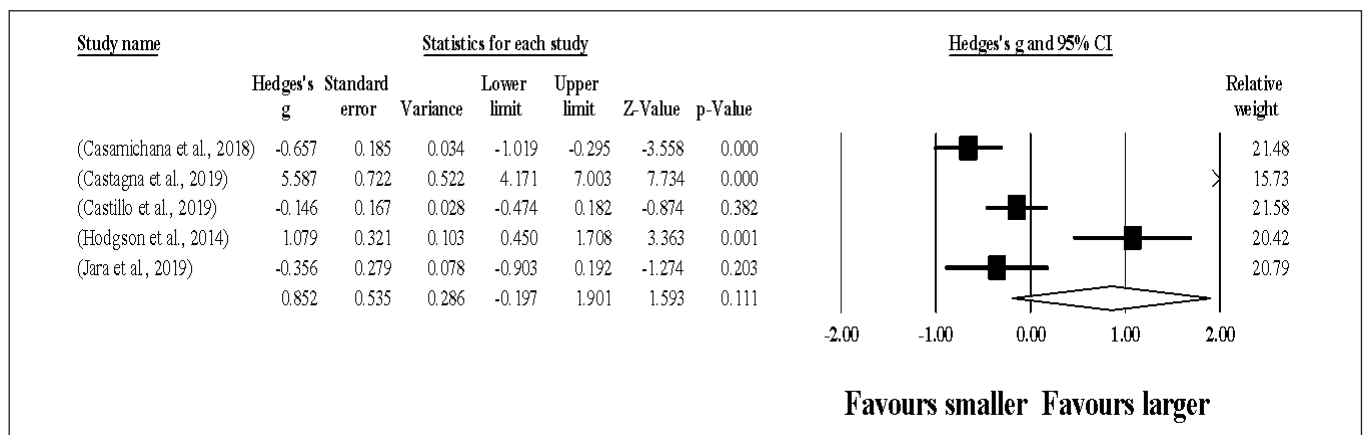


FIG. 7. Forest plot of changes in deceleration actions, in soccer players participating in small-sided games using smaller compared to larger pitch sizes. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical relative weight of the study. The white diamond reflects the overall result.

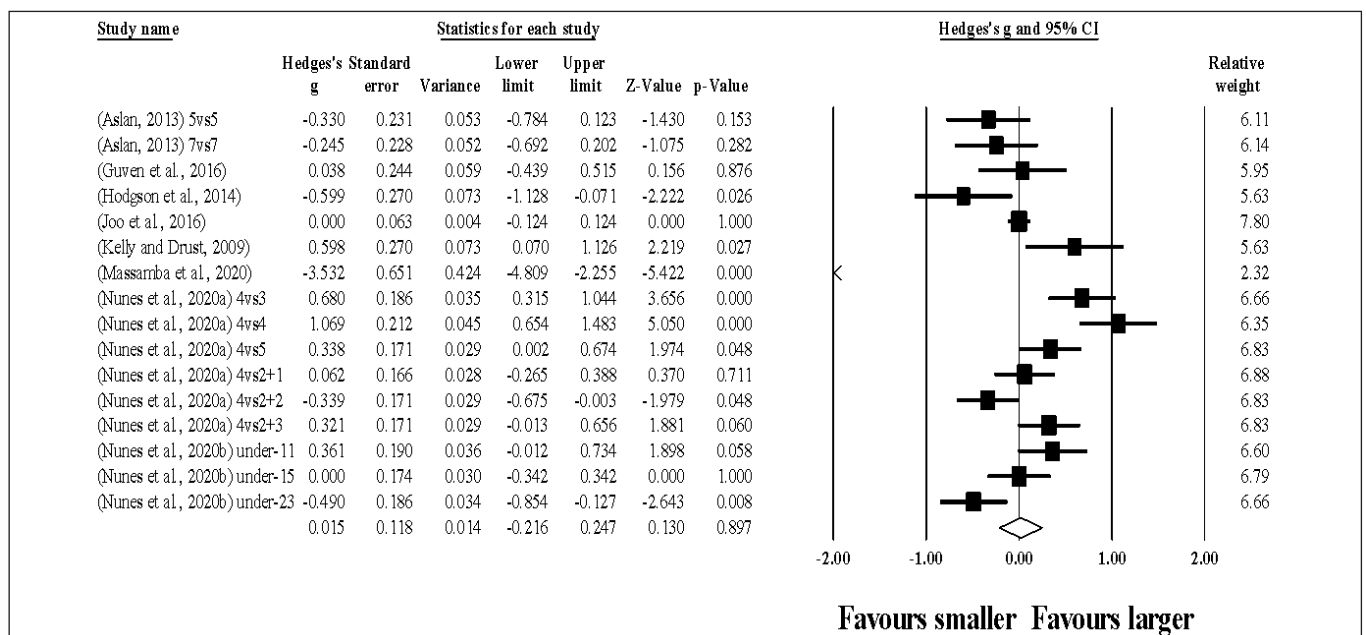


FIG. 8. Forest plot of changes in passes, in soccer players participating in small-sided games using smaller compared to larger pitch sizes. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical relative weight of the study. The white diamond reflects the overall result.

TABLE 7. Summary of the included studies and results of technical execution in smaller and larger pitch sizes.

Study	Format	Age category	N	Variable	Smaller Mean $\pm$ SD	Larger Mean $\pm$ SD	Larger-Smaller (%) [*]	Tendency of change	Included in the meta-analysis
[71]	5vs.5 + GK	Adults	10	Dribbles	13.9 $\pm$ 7.9	15.6 $\pm$ 6.8	12.2	Increase in larger pitch size	Yes
[71]	7vs.7 + GK	Adults	10	Dribbles	12.1 $\pm$ 6.5	11.3 $\pm$ 6.6	-6.6	Decrease in larger pitch size	Yes
[71]	5vs.5 + GK	Adults	10	Passes	32.8 $\pm$ 12.6	28.6 $\pm$ 9.0	-12.8	Decrease in larger pitch size	Yes
[71]	7vs.7 + GK	Adults	10	Passes	29.5 $\pm$ 9.6	26.9 $\pm$ 9.8	-8.8	Decrease in larger pitch size	Yes
[40]	5vs.5 + GK	Youth ^f	10	Dribbles	5.2 $\pm$ 1.7	1.7 $\pm$ 0.8	-67.3	Decrease in larger pitch size	Yes
[40]	5vs.5 + GK	Youth ^f	10	Passes	14.5 $\pm$ 6.6	18.7 $\pm$ 4.3	29.1	Increase in larger pitch size	No. Reason: results are the same as presented in the [40]
[18]	5vs.5 + GK	Youth ^f	10	Dribbles	5.2 $\pm$ 1.7	1.7 $\pm$ 0.8	-67.3	Decrease in larger pitch size	No. Reason: results are the same as presented in the [40]
[18]	5vs.5 + GK	Youth ^f	10	Passes	14.5 $\pm$ 6.6	18.7 $\pm$ 4.3	29.1	Increase in larger pitch size	No. Reason: results are the same as presented in the [40]
[84]	4vs.4	Adults	8	Dribbles	11.3 $\pm$ 8.5	12.8 $\pm$ 10.2	13.3	Increase in larger pitch size	Yes
[84]	4vs.4	Adults	8	Passes	74.6 $\pm$ 27.2	76.0 $\pm$ 35.3	1.9	Increase in larger pitch size	Yes
[61]	5vs.5 + GK	Youth ⁱ	8	Dribbles	7.1 $\pm$ 2.6	6.9 $\pm$ 2.9	-2.8	Decrease in larger pitch size	Yes
[61]	5vs.5 + GK	Youth ⁱ	8	Passes	23.1 $\pm$ 4.8	20.1 $\pm$ 3.0	-12.9	Decrease in larger pitch size	Yes
[87]	5vs.5 + GK	Youth ^g	3	Passes	14 $\pm$ NR	8 $\pm$ NR	-42.9	Decrease in larger pitch size	No. Reason: no reported SD
[39]	8vs.8 + GK	Youth ^b	149	Passes	13.8 $\pm$ 5.2	13.8 $\pm$ 6.4	0.0	No differences	Yes
[17]	5vs.5 + GK	Youth ^h	8	Passes	71.5 $\pm$ 10.2	79.9 $\pm$ 13.5	11.7	Increase in larger pitch size	Yes
[17]	5vs.5 + GK	Youth ^h	8	Dribbles	53.0 $\pm$ 10.1	62.2 $\pm$ 9.3	17.4	Increase in larger pitch size	Yes
[92]	5vs.5	Youth ^c	10	Passes	18.6 $\pm$ 1.9	11.7 $\pm$ 1.6	-37.1	Decrease in larger pitch size	Yes
[92]	5vs.5	Youth ^c	10	Dribbles	3.4 $\pm$ 0.8	3.6 $\pm$ 1.0	5.9	Increase in larger pitch size	Yes
[62]	4vs.3	Youth ⁱ	20	Passes	9.3 $\pm$ 3.5	12.8 $\pm$ 5.4	37.6	Increase in larger pitch size	Yes
[62]	4vs.4	Youth ⁱ	20	Passes	6.3 $\pm$ 3.2	10 $\pm$ 3.5	58.7	Increase in larger pitch size	Yes
[62]	4vs.5	Youth ⁱ	20	Passes	7.3 $\pm$ 3.8	8.8 $\pm$ 4.6	20.5	Increase in larger pitch size	Yes
[62]	4vs.2 + 1	Youth ⁱ	20	Passes	9.0 $\pm$ 4.0	9.3 $\pm$ 3.8	3.3	Increase in larger pitch size	Yes
[62]	4vs.2 + 2	Youth ⁱ	20	Passes	8.0 $\pm$ 3.2	9.3 $\pm$ 3.8	16.3	Decrease in larger pitch size	Yes
[62]	4vs.2 + 3	Youth ⁱ	20	Passes	9.0 $\pm$ 4.0	10.3 $\pm$ 3.2	14.4	Increase in larger pitch size	Yes
[93]	4vs.4	Youth ^a	16	Passes	8.7 $\pm$ 4.9	11.3 $\pm$ 7.4	29.9	Increase in larger pitch size	Yes
[93]	4vs.4	Youth ^e	18	Passes	7.1 $\pm$ 3.1	7.1 $\pm$ 2.7	0.0	No differences	Yes
[93]	4vs.4	Youth ⁱ	18	Passes	8.0 $\pm$ 3.6	6.0 $\pm$ 4.1	-25.0	Decrease in larger pitch size	Yes

SD: standard-deviation; %: percentage of difference; a: Under-11 group; b: Under-12; group; c: Under-13 group; d: Under-14 group; e; under-15 group; f: under-16 group; g: under-17 group; h: under-18 group; i: under-23 group; NR: non-reported

$p < 0.001$; $I^2 = 71.8\%$) formats, with significant sub-group difference between formats ($p = 0.009$).

The HSR was greater at larger compared to smaller pitches when SSGs were played by young/youth (31 study groups; $ES = 1.16$; $p < 0.001$; $I^2 = 94.6\%$) and adult players (4 study groups; $ES = 1.53$; $p = 0.001$; $I^2 = 87.7\%$), without significant sub-group difference according to the age of the soccer players ($p = 0.423$).

Due to the limited number of study groups available for each moderator category, robust moderator analyses were precluded for ACC and DEC.

Smaller vs. larger pitch sizes during SSG: effects on technical execution

A summary of the included studies and results of technical execution (passes and dribbles) reported in smaller and larger SSGs are provided in Table 7.

Sixteen study groups provided data for passes, involving 16 smaller and 16 larger pitch sizes being compared (pooled $n = 375$).

Results (Figure 8) showed that SSGs played at larger pitches induced similar passes compared to smaller pitches ($ES = 0.02$, trivial; 95% $CI = -0.22$ to 0.25 ; $p = 0.897$; $I^2 = 85.2\%$; Egger's test $p = 0.640$, with a corrected value equal to the observed value; supplementary Figure 7). Seven study groups provided data for dribbling, involving 7 smaller and 7 larger pitch sizes being compared (pooled $n = 64$). Results (Figure 9) showed that SSGs played at larger pitches induced similar dribbles compared to smaller pitches ($ES = -0.05$, trivial; 95% $CI = -0.50$ to 0.40 ; $p = 0.823$; $I^2 = 82.0\%$; Egger's test $p = 0.159$, with a corrected value of $ES = -0.29$, 95% $CI = -0.76$ to 0.18 ; supplementary Figure 8).

Moderator analyses

The passes were similar at larger compared to smaller pitches when SSGs were played with either small (10 study groups; $ES = 0.20$; $p = 0.153$; $I^2 = 82.5\%$) and medium (6 study groups; $ES = -0.42$; $p = 0.102$; $I^2 = 87.9\%$) formats, with significant sub-group difference between formats ($p = 0.034$).

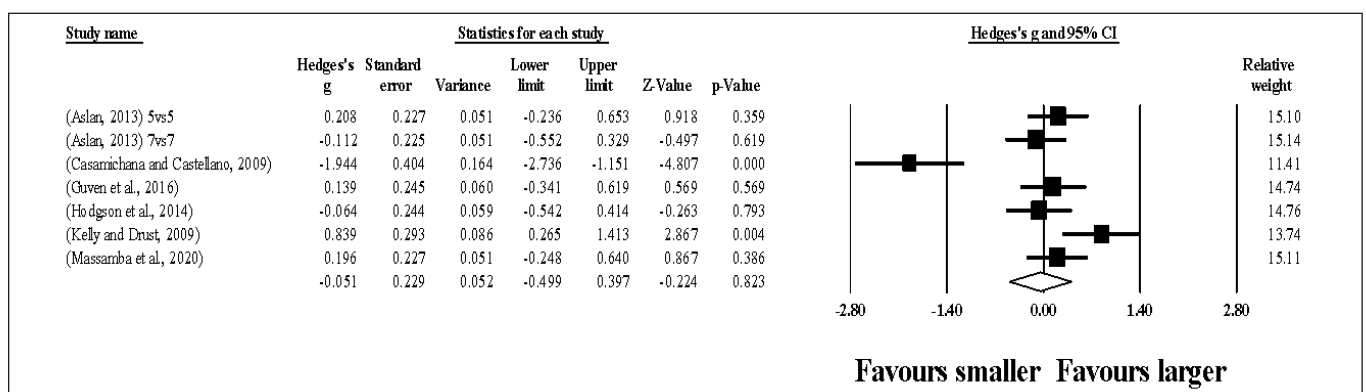


FIG. 9. Forest plot of changes in dribbles, in soccer players participating in small-sided games using smaller compared to larger pitch sizes. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical relative weight of the study. The white diamond reflects the overall result.

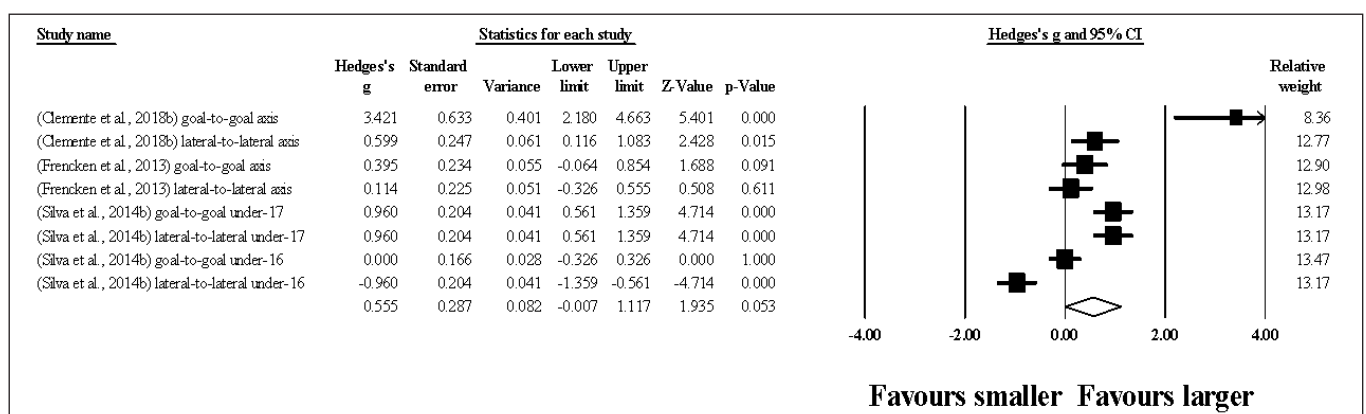


FIG. 10. Forest plot of changes in centroid, in soccer players participating in small-sided games using smaller compared to larger pitch sizes. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical relative weight of the study. The white diamond reflects the overall result.

TABLE 8. Summary of the included studies and results of tactical behavior in smaller and larger pitch sizes.

Study	Format	Age category	N	Variable	Smaller Mean $\pm$ SD	Larger Mean $\pm$ SD	Larger-Smaller (%)	Tendency of change	Included in the meta-analysis
[13]	7vs.7 + GK	Youth ^c	14	Stretch index	8.6 $\pm$ 1.7	11.5 $\pm$ 2.3	33.7	Increase in larger pitch size	Yes
[13]	7vs.7 + GK	Youth ^d	14	Stretch index	8.6 $\pm$ 2.5	10.1 $\pm$ 2.0	17.4	Increase in larger pitch size	Yes
[68]	11vs.11 + GK	Adults	10	Spatial exploration index	85.1 $\pm$ 1.6	68.6 $\pm$ 9.2	-19.4	Decrease in larger pitch size	No Reason: less than 3 studies reported the outcome
[81]	11vs.11 + GK	Adults	10	Stretch index	35.5 $\pm$ 9.5	45.8 $\pm$ 7.8	29.01	Increase in larger pitch size	Yes
[81]	11vs.11 + GK	Adults	10	Centroid (g)	24.5 $\pm$ 8.4	58.6 $\pm$ 9.6	139.2	Increase in larger pitch size	Yes
[81]	11vs.11 + GK	Adults	10	Centroid (l)	33.1 $\pm$ 6.1	36.8 $\pm$ 3.9	11.2	Increase in larger pitch size	Yes
[69]	4vs.4 + GK	Adults	10	Surface area	38 $\pm$ 31	34 $\pm$ 29	-10.5	Decrease in larger pitch size	Yes
[69]	4vs.4 + GK	Adults	10	Centroid (g)	1.5 $\pm$ 1.1	2.0 $\pm$ 1.2	33.3	Increase in larger pitch size	Yes
[69]	4vs.4 + GK	Adults	10	Centroid (l)	1.0 $\pm$ 0.8	1.1 $\pm$ 0.8	10.0	Increase in larger pitch size	Yes
[88]	5vs.5 + GK	Adults	3	Spatial exploration index	2.2 $\pm$ 0.3	3.2 $\pm$ 0.4	45.5	Increase in larger pitch size	No Reason: less than 3 studies reported the outcome
[88]	5vs.5 + GK	Adults	3	Predictive Ellipse Area	67.6 $\pm$ 18.8	129.1 $\pm$ 46.5	91.0	Increase in larger pitch size	No Reason: less than 3 studies reported the outcome
[88]	5vs.5 + GK	Adults	3	Standard Ellipse Area	11.3 $\pm$ 3.1	21.4 $\pm$ 7.8	89.4	Increase in larger pitch size	No Reason: less than 3 studies reported the outcome
[66]	4vs.4 + GK	Youth ^c	36	Surface area	84.5 $\pm$ 8.7	143.2 $\pm$ 23.9	69.5	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ^c	36	Stretch index	4.6 $\pm$ 0.4	5.9 $\pm$ 1.8	28.3	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ^c	36	Width per length ratio	1.0 $\pm$ 0.2	1.1 $\pm$ 0.3	10.0	Increase in larger pitch size	No Reason: less than 3 studies reported the outcome
[66]	4vs.4 + GK	Youth ^e	43	Surface area	94.8 $\pm$ 11.1	158.3 $\pm$ 34.2	67.0	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ^e	43	Stretch index	5.1 $\pm$ 0.4	6.2 $\pm$ 0.8	21.6	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ^e	43	Width per length ratio	0.9 $\pm$ 0.2	1.1 $\pm$ 0.3	22.2	Increase in larger pitch size	No Reason: less than 3 studies reported the outcome
[66]	4vs.4 + GK	Youth ^g	28	Surface area	115.5 $\pm$ 30.9	146.4 $\pm$ 22.3	26.8	Increase in larger pitch size	Yes

TABLE 8. Continue.

Study	Format	Age category	N	Variable	Smaller Mean $\pm$ SD	Larger Mean $\pm$ SD	Larger-Smaller (%)	Tendency of change	Included in the meta-analysis
[66]	4vs.4 + GK	Youth ^g	28	Stretch index	5.3 $\pm$ 0.7	6.0 $\pm$ 0.6	13.2	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ^g	28	Width per length ratio	1.0 $\pm$ 0.1	1.1 $\pm$ 0.1	10.0	Increase in larger pitch size	No Reason: less than 3 studies reported the outcome
[66]	4vs.4 + GK	Youth ⁱ	43	Surface area	101.2 $\pm$ 18.2	140.9 $\pm$ 27.0	39.2	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ⁱ	43	Stretch index	5.2 $\pm$ 0.6	5.9 $\pm$ 0.6	13.5	Increase in larger pitch size	Yes
[66]	4vs.4 + GK	Youth ⁱ	43	Width per length ratio	0.9 $\pm$ 0.2	1.0 $\pm$ 0.2	11.1	Increase in larger pitch size	No Reason: less than 3 studies reported the outcome
[58]	4vs.4 + GK	Youth ^g	20	Width per length ratio	1.1 $\pm$ 0.1	1.1 $\pm$ 0.2	0.0	No differences	No Reason: less than 3 studies reported the outcome
[58]	4vs.4 + GK	Youth ^g	20	Surface area	119.5 $\pm$ 13.5	247.7 $\pm$ 44.6	107.3	Increase in larger pitch size	Yes
[58]	4vs.4 + GK	Youth ^g	20	Centroid (g)	0.5 $\pm$ 0.1	0.6 $\pm$ 0.1	20.0	Increase in larger pitch size	Yes
[58]	4vs.4 + GK	Youth ^g	20	Centroid (l)	0.4 $\pm$ 0.1	0.5 $\pm$ 0.1	25.0	Increase in larger pitch size	Yes
[58]	4vs.4 + GK	Youth ^f	20	Width per length ratio	1.0 $\pm$ 0.5	1.5 $\pm$ 0.2	50.0	Increase in larger pitch size	No Reason: less than 3 studies reported the outcome
[58]	4vs.4 + GK	Youth ^f	20	Surface area	121.2 $\pm$ 24.6	251.2 $\pm$ 46.3	107.3	Increase in larger pitch size	Yes
[58]	4vs.4 + GK	Youth ^f	20	Centroid (g)	0.5 $\pm$ 0.1	0.5 $\pm$ 0.1	0.0	No differences	Yes
[58]	4vs.4 + GK	Youth ^f	20	Centroid (l)	0.5 $\pm$ 0.1	0.4 $\pm$ 0.1	-20.0	Decrease in larger pitch size	Yes
[97]	6vs.6	Youth ^e	24	Surface area	23.9 $\pm$ 7.0	28.8 $\pm$ 9.1	20.5	Increase in larger pitch size	Yes

SD: standard-deviation; g: goal-to-goal; l: lateral-to-lateral; %: percentage of difference; a: Under-11 group; b: Under-12; group; c: Under-13 group; d: Under-14 group; e; under-15 group; f: under-16 group; g: under-17 group; h: under-18 group; i: under-23 group

Due to the limited number of study groups available for each age category, robust moderator analyses were precluded for passes and dribbles, and the same for format of play in dribbles.

Smaller vs. larger pitch sizes during SSG: effects on tactical behavior

A summary of the included studies and results of tactical behavior (centroid, stretch index and surface area) reported in smaller and larger SSGs are provided in Table 8.

Eight study groups provided data for centroid, involving 8 smaller and 8 larger pitch sizes being compared (pooled $n = 120$). Results (Figure 10) showed that SSGs played at larger pitches induced similar centroid compared to smaller pitches ($ES = 0.56$, small; 95% CI = -0.01 to 1.12; $p = 0.053$; $I^2 = 92.2\%$; Egger's test $p = 0.151$, with a corrected value of $ES = 0.81$, 95% CI = 0.11 to 1.51; supplementary Figure 9).

Seven study groups provided data for stretch index, involving 7 smaller and 7 larger pitch sizes being compared (pooled $n = 188$).

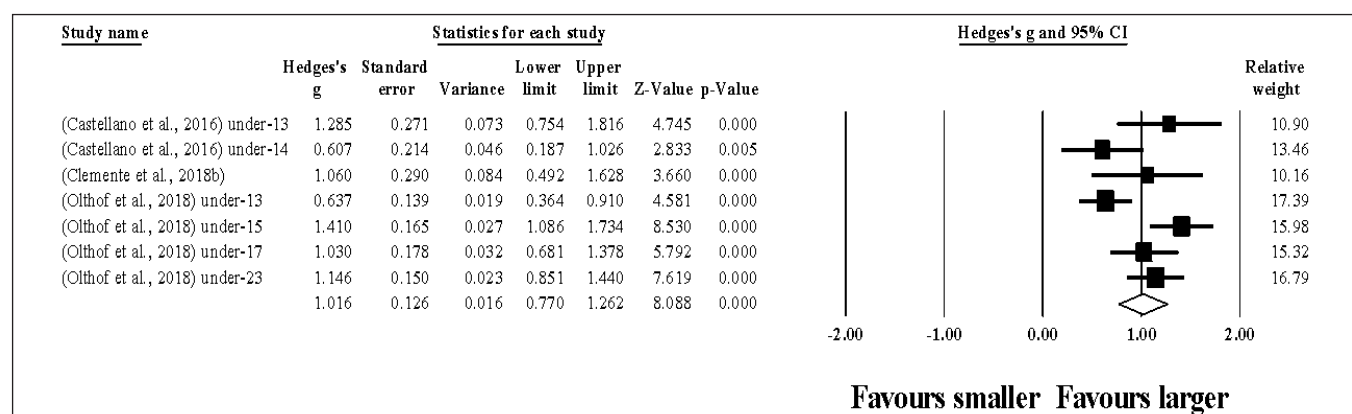


FIG. 11. Forest plot of changes in stretch index, in soccer players participating in small-sided games using smaller compared to larger pitch sizes. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical relative weight of the study. The white diamond reflects the overall result.

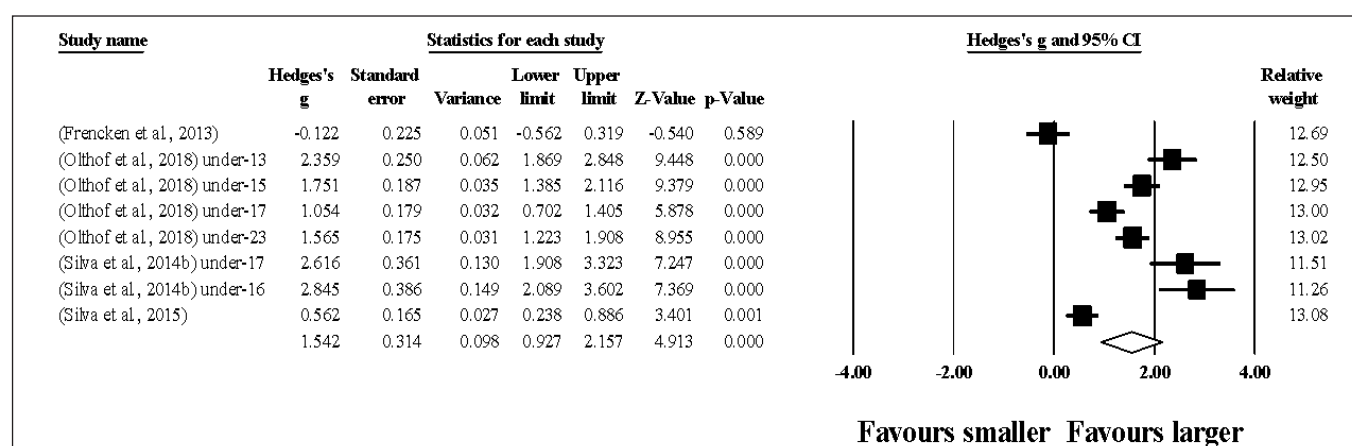


FIG. 12. Forest plot of changes in surface area, in soccer players participating in small-sided games using smaller compared to larger pitch sizes. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical relative weight of the study. The white diamond reflects the overall result.

Results (Figure 11) showed that SSGs played at larger pitches induced greater stretch index compared to smaller pitches ($ES = 1.02$, moderate; 95% CI = 0.77 to 1.26; $p < 0.001$; $I^2 = 67.5\%$; Egger's test $p = 0.701$, with a corrected value of $ES = 0.89$, 95% CI = 0.63 to 1.15; supplementary Figure 10).

Eight study groups provided data for surface area, involving 8 smaller and 8 larger pitch sizes being compared (pooled $n = 224$). Results (Figure 12) showed that SSGs played at larger pitches induced greater surface area compared to smaller pitches ($ES = 1.54$, large; 95% CI = 0.93 to 2.16; $p < 0.001$; $I^2 = 94.0\%$; Egger's test $p = 0.164$, with a corrected value of $ES = 1.38$, 95% CI = 0.78 to 1.97; supplementary Figure 11).

Moderator analyses

Due to the limited number of study groups available for each moderator category, robust moderator analyses were precluded for centroid, stretch index and surface area.

DISCUSSION

The current findings of this systematic review and meta-analysis revealed a meaningful effect of changing the pitch size in the physiological, physical, and tactical responses of soccer players during SSGs. Such an effect was not verified in technical responses.

Smaller vs. larger pitch sizes during SSGs: Effects on physiological responses

The current systematic review and meta-analysis revealed that larger pitches meaningfully intensified exercise, reflected by the HR responses and RPE values of players. Additionally, a sub-group analysis revealed that this evidence was also significant in small, medium, and large formats of play, as well as in youth and adult players. Despite the high heterogeneity levels of meta-analysis and the experimental differences considering the pitch sizes, it was clear that larger pitch sizes generated greater HR (38 out of 42 study groups included) and RPE levels (33 out of 36 study groups included).

Larger pitches were between 1.1x [39] and 3.7x [40] bigger than the smaller pitches, and all formats of play were covered.

It is reasonable to expect that greater physiological responses would occur in larger pitches since there more space to cover, albeit with less spatial exploration variability. However, larger pitches may make the game more structured [20] even though the space available allows each player to cover greater distances at a faster pace. This fact was confirmed in the current meta-analysis, as significantly greater distances were covered and greater dispersion between teammates was found on larger pitches. HR and RPE reflect external load demands [41], which could explain the meaningful physiological intensification occurring on larger pitches. Additionally, the fact that RPE is conditioned both by HR and external load demands (in particular, total distance) [42] further explains the association between larger pitches and higher HR and RPE scores.

Comparisons between larger and smaller pitch sizes were also executed while considering the format of play as moderators (formats of play were classified as small – 2 vs. 2 to 4 vs. 4; medium – 5 vs. 5 to 8 vs. 8; and large – 9 vs. 9 to 11 vs. 11). Interestingly, increasing the pitch size had similar effects in all formats (i.e., HR and RPE were significantly increased). Similarly, youth and adult players alike presented significantly greater values of HR and RPE on larger pitch sizes. Therefore, it can be argued that larger pitches foster more intense exercise than smaller pitches independent of the format of play or age group.

Smaller vs. larger pitch sizes during SSGs: Effects on physical demands

The representative learning design and manipulation of task constraints are important pedagogical principles that coaches and practitioners should consider while planning training sessions [43]. Smaller and/or larger pitch sizes during SSGs can be utilized to achieve the main goal of the session. It is also known that the size of the pitch can be managed to simulate more or less the demands of the match. As an example, in a recent study [44], it was found that larger pitch sizes 156 to 182 m² were the most similar to replicate match demands regarding the total distance, high-speed running, very high speed running, and sprinting.

For example, the results of our meta-analysis showed that SSGs played at larger pitches (range length: 30–108 m; range width: 20–68 m; range area per player: 37.5–334 m²) induced greater TD and HSR values than smaller configurations (range length: 10–68 m; range width: 13–68 m; range area per player: 15.6–199.75 m²), independent of the format of play and age. In addition, similar ACC and DEC values were observed during SSGs played on larger and smaller pitches.

A moderator analysis of the current study showed that high values of area per player (e.g., 300 m²) and reduced number of players (e.g., 7 vs. 7) increased the physical demands imposed on players during SSGs [14]. These findings should be considered by coaches during training planning, especially in youth academies and on

training days before matches. A previous study demonstrated that simultaneously reducing absolute and relative area per player induced a higher frequency of offensive unity and increased the level of interaction between teammates [45]. Therefore, the increase in tactical performance and reduced physical demands (TD and HSR) during SSGs played with a low relative area per player suggest that this configuration can be beneficial in training sessions designed for youth and adult players of a low skill level, as the levels of task difficulty and complexity are easier to adjust [46]. On the other hand, according to the development of physical fitness and tactical skills, coaches and practitioners can increase the pitch size and formats. In addition, previous studies found that coaches periodized training contents to attain the highest weekly training load in the middle of the week (e.g., three days before a match) [47, 48]. Therefore, especially regarding starters (e.g., players who participate for at least 75 min in official matches), SSGs played on larger pitches are recommended in the middle of the week.

In youth and professional players, high-intensity activities (e.g., HSR and sprinting) are important physical variables in official matches [49–51]. In fact, using meta-analytical procedures, the current study provided robust conclusions about the advantages of larger SSGs in increasing TD and HSR compared to smaller SSGs. However, previous studies have provided a critical discussion about the specificity and representativeness of SSGs to stimulate the physical demands of official matches, which is worthy of further discussion [52]. Players tend to perform fewer high-intensity activities (e.g., > 19.8 km·h⁻¹ or > 25.2 km·h⁻¹) in SSGs than in official matches [53]. In contrast, accelerometry-based variables increase during SSGs [54] and achieve similar values to the peak periods of official matches [55]. Therefore, regarding physical demands, SSGs are not the same as official matches. External load monitoring and complementary exercise approaches (e.g., generic high-intensity running exercises) could be useful to ensure that distance- and accelerometry-based outcomes are achieved throughout the season [56]. Naturally, interactions of pitch sizes with other task constraints as rule modifications may produce different results for coaches. As an example, a recent study revealed that including mini-goals vs. using a ball possession match lead to lower values in physical demands [57].

Smaller vs. larger pitch sizes during SSGs: Effects on technical execution

Analyzing the differences in the technical actions performed by players under different SSG rules may help coaches improve the propensity of the task to the main goal of the session. Knowledge on the impact of pitch size alterations on players' technical execution is useful for better pedagogical planning. The results of the current systematic review and meta-analysis showed that the frequency of technical actions is not influenced by changing the pitch size.

Differences in tactical [58], physiological [59], and physical [60] responses were observed when the pitch size was changed. Also, smaller pitches seem to induce players to reduce the interpersonal

distances between them. Together, these two factors could lead to differences in technical execution when the pitch size is manipulated, which contrasts the current results. The heterogeneity of the data and the type of variable measured are two main factors that might contribute to this effect.

Regarding the heterogeneity of the data, some studies indicated that the numbers of passes [61] and dribbles [40] are higher for SSGs played on smaller pitches, while others showed that these values are higher on larger pitches [17, 62]. We argue that other rules might have biased the results, leading to high heterogeneity. Specifically, the presence of a goalkeeper, the adoption of the offside rule, and the presence of floaters are examples of rules that were not homogeneously adopted across studies. For example, a previous study showed that numerically balanced SSGs required players to dribble more frequently than in formats with floaters [63]. Even though the smaller pitches brought players closer together (thus facilitating the execution of passes), the numerically balanced condition might have encouraged players to dribble instead of pass. Therefore, these contradictory effects, when expanded to other possible manipulations, might explain the high heterogeneity among results and the failure of some studies to detect an influence of changing the pitch size on technical execution.

Moreover, technical execution was primarily measured by accounting for the frequency of the events. Although this approach allows coaches to understand the propensity of each SSG to stimulate the main outcome of the session, it neglects the quality of the technical executions observed. Thus, coaches must also consider players' skill levels [64] and task complexity [65] when deciding which formats to choose. Specifically, the same frequencies of technical actions could be observed even if differences in the quality of the execution are hidden. For example, since the players are closer to each other on smaller pitches [66], a higher percentage of successful passes could be expected, although dribbling could become more difficult because there is less available space. These results are not measurable by the current methodology, as most of the studies accounted only for the frequency and not the quality of technical actions. Therefore, adopting a contextual analysis of technical execution that includes performance indicators for each variable and accounts for skill efficacy and efficiency remains a challenge for future researchers in this topic.

Smaller vs. larger pitch sizes during SSGs: Effects on tactical behavior

The selected studies on tactical behavior considered positional variables, collected by tracking techniques using devices such as GPS and LPM systems [58, 66]. All tactical variables were continuously measured during the SSGs and represent both with- and without-the-ball behaviors. These results revealed no differences in the centroid position when changing the pitch size. While, larger pitches induced higher values of the stretch index and surface area.

A previous study on this topic has shown that when a specific axis of the field (e.g., depth) is increased, the players tend to increase

their exploration towards that axis [67], even if the relative area per player remains the same. This means that increases in the pitch size as a whole (not just on one axis) are expected to increase the spatial exploration along both axes—this explains the observed increase in the stretch index and the surface area in larger pitches. The larger the pitch, the further the players are expected to be from each other to cover larger distances to create scoring opportunities when attacking and prevent them when defending. On the other hand, no differences in the centroid position were observed when the pitch size was altered. In the current study, goal-to-goal and lateral-to-lateral axes were analyzed together due to the small sample, which might explain the absence of differences. Specifically, the goal-to-goal centroid difference seems to be more strongly affected by changing the pitch size than the lateral axis distance [58, 68, 69]. In the future, when more studies on each variable are available, a new investigation on this topic is recommended to test this hypothesis.

The positional differences resulting from changing the pitch size should be considered by coaches when designing training tasks using SSGs. Specifically, increasing the pitch size seems to increase the difficulty that players face when attempting to adequately occupy the most relevant spaces on the pitch. At this point, adjusting the tactical complexity to players' current level is recommended [65]. For this reason, the increase in pitch size could be understood as a task constraint that should be progressively applied as the players get used to one specific format. In other words, when teaching young groups or introducing new tactical content to experienced groups, it could be beneficial to facilitate the tactical occupation by adopting smaller pitches—the pitch size can later be enlarged according to the development of players' tactical skills on small pitches. Supporting this assumption, a previous study showed that enlarging the pitch size reduces the number of interactions that occur during SSGs [45]. This is a strong indicator of difficulty to adopt more complex offensive strategies when the pitch size is increased.

Limitations, future research, and practical applications

Besides its contribution to the training process in soccer, the current review has limitations that must be considered. First, the high heterogeneity of the studies might be considered, as comparing studies methodologically different can increase the risk of bias. Therefore, a more in-depth investigation of SSGs is recommended to include studies with more similar experimental designs, thus reducing this bias. Also, none of the studies achieved a two-point score in the methodological quality assessment. This indicates that studies on SSGs should improve their methodology quality to adequately investigate the phenomenon. This issue is a challenge when conducting studies with high ecological validity, although recent advances in players' monitoring allow better control of intervening variables when the SSGs are prescribed alongside regular training. Still, better descriptions of experimental protocols will increase the reproducibility of studies and, hence, improve the methodological quality of future research by allowing the replication of designs under different task

conditions. It seems also important to emphasize the development of studies on the technical and tactical dimensions, as the small number of studies did not allow us to conduct a moderator analysis in the current systematic review. Finally, it seems important to consider the natural human variation occurring in SSGs which may play an important bias in case of no repeating measures in the experiments or in case of a high noise which may induce different results based on player's participation [70].

In practical settings, SSGs with larger pitch sizes (e.g., > 250 m² per player) can increase the physical demands imposed on players, especially TD and HSR. Considering that coaches periodize training contents in such a way that training load is increased until three days before the next match, larger pitches can be better during the middle of the week. In contrast, smaller pitches with optimal acceleration loads can be a good option at the beginning of the week and/or until two days before the next match. In addition, SSGs with reduced load demands (e.g., smaller pitches associated with other task constraints) can facilitate the engagement of low-level young groups during training sessions.

Practical implications can be proposed concerning tactical and technical dimensions. Specifically, increasing the pitch size is not intended to impact the frequency of technical actions, although it significantly increases players' area of occupation on the pitch. For this reason, smaller pitches should be preferably adopted in young groups, which will characterize a facilitated task condition and allow players to explore tactical solutions for emerging problems. On the other hand, larger pitches will create a challenging environment in which the spatial occupation will be more difficult, which can emphasize the development of collective tactical principles related to concentration and space creation.

CONCLUSIONS

This systematic review revealed a clear effect of larger pitch sizes for increasing the intensification of internal load responses (HR and RPE), distances covered (total and HSR), and promoting the dispersion of players at a collective level (stretch index and surface area). These results were confirmed independently of the format of play and age group in terms of internal load and external load. Despite the heterogeneity of the pool of included articles, the individual results of each study provided clear support for these findings. On the other

hand, meaningful differences were not evident between pitch sizes in terms of the numbers of accelerations, decelerations, passes, or dribbles performed. Based on the available evidence, larger pitch sizes can be recommended to increase the physiological and physical intensities of SSGs and promote collective dynamics occupying greater space to distance players.

Conflicts of interest/Competing interests

The authors declare that they have no conflicts of interest relevant to the content of this review.

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Authorship Contributions

FMC lead the project, wrote and revised the original manuscript. RRC analyzed and interpreted the data, wrote the statistical report and revised the original manuscript. FMC, HS and MRG run the data search, performed the methodological assessment, conducted the data extraction, wrote and revised the original manuscript. GMP, RA, DC, JRG, RS and AFS wrote and revised the original manuscript.

Conflict of interest

The authors declared no conflict of interest.

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A comparison of running and contact loads in U18 and U20 international rugby union competition

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ABSTRACT: The purpose of the present study was to characterize and compare locomotor and contact loads in U18 and U20 international rugby union competition during matches, and specifically during peak match-play phases using short rolling epochs and continuous ball-in-play (BIP) sequences. 20 international matches from French national teams were analysed in the U18 and U20 Six Nations Tournament respectively and World Rugby U20 Championship. Running loads were quantified using global positioning devices (16 Hz) and contact loads via video match analysis software. Players were split into forward (U18, $n = 29$; U20, $n = 32$) and back positional groups (U18, $n = 20$; U20, $n = 24$). Compared with U20 peers, U18 players covered a higher total distance (effect size (ES) = -0.76 ± 0.25) and at high-speeds per minute ($> 4 \text{ m} \cdot \text{s}^{-1}$; ES = -0.55 ± 0.25) and performed more accelerations (ES = -0.71 ± 0.25). While a greater frequency of BIP sequences $> 90 \text{ s}$ duration was observed in U20s versus U18s match-play, U18s covered more total distance and high-speed distance (ES = -0.42 ± 0.13 and -0.33 ± 0.13 respectively) per minute during these longer sequences. During peak rolling phases shorter than 4 minutes, no clear differences existed between age categories in running activity, while U20 forwards performed more contact actions than U18 peers. The match-play loads observed in the present international U18 players suggest that they are ready to respond to the overall and peak demands observed in U20 competition. Moreover, the present information on peak activity phases can aid design of overload high-intensity conditioning sessions to respond to the running- and contact-demands identified in those competitions.

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INTRODUCTION

Rugby Union is considered one of the most intense and physically demanding team sport games [1]. At elite senior standards, a comprehensive body of research has quantified the physical characteristics in match-play [2, 3, 4, 5, 6]. Analyses using micro-sensor technology such as Global Positioning Systems (GPS) show that the game is intermittent in nature [7]. Players perform frequent bouts of high-speed running and participate in intense physical collisions such as tackling and static actions including scrums, rucks and mauls [8]. In contrast, less information [9, 10] exists on the demands in younger elite players, notably in international competition and how these potentially evolve across different age categories. A comparison of U18 versus U20 amateur rugby union competition reported greater distances per minute

covered by players in the former age category [9]. However, studies of U18 competition have mostly considered English players performing at U18 county or school level [9, 10, 11]. Accordingly, a comparison of external load (locomotor and physical contact events) in international U18 versus U20's competition would provide some answers on whether participation at U18 standards provides an appropriate platform for preparing players physically for U20's standards. In addition, limited knowledge on whether movement demands in U20s international match-play are sufficient to prepare players for senior international rugby [12]. Such information could notably help in targeting the specific physical qualities and outputs that younger players need to work on to continue their progression [12].

A substantial number of studies have reported the average game-play demands of rugby union, generally over 80-minutes or across playing halves [4, 13]. Yet given the fluctuating nature of running demands, whole-match averages do not reflect the peak intensities reached intermittently during pivotal phases throughout play. Knowledge of efforts during peak match-play periods provides information to help prepare players physically to face the most demanding requirements of competition; frequently known as ‘worst-case scenario’ phases [14]. Training volume and intensity can be specifically referenced against these peak periods of activity to ensure the desired physical stimulus is reached for both the group as a whole and across playing positions. Two methods are generally used to provide key insights into the more demanding periods of play: physical efforts during short epochs – both fixed and rolling, usually of 1 to 10 mins duration [15, 16], and continuous ball-in-play (BIP) sequences determined according to the entire duration of the sequence [13, 17, 18, 19]. Irrespective of the method employed, these epochs typically demonstrate substantial differences compared to average whole match demands. However, while rugby union is a contact-dominant team sport, to our knowledge, no study has attempted to characterize and compare peak demands for locomotor activity and physical collision events concomitantly, and particularly in international U18 and U20 competition. Such information could be used as a foundation for fashioning isolated physical conditioning drills and small-sided games both generally and for positional groups specifically in younger categories.

The propose of the present study was to characterize and compare locomotor and contact loading in U18 and U20 international rugby union competition for the whole-match and during phases of peak match-play activity including both continuous BIP sequences and short rolling epochs. Accounting for findings in a review by Till *et al.* [20], showing that younger players perform higher running loads at school or academy level, it was hypothesized that even at international level U18 players would perform more locomotor activity than U20 peers whereas the latter would perform more contact-events [20].

MATERIALS AND METHODS

Experimental Approach

External loads represented by both running activity and physical contact events were investigated in international French U18 and U20 youth rugby union players during official match-play using GPS and video match analysis software (SportsCode). Data were collected in 20 international matches: the U18's played 9 matches during the U18 Six Nations Tournament (7 matches) and Aon® U18 International Series (2 matches) while the U20's played a total of 11 matches of which 9 were in the U20 Six Nations Tournament and 2 in the World Rugby U20 Championship. Data were collected in matches in these tournaments across three successive seasons: 2016/2017, 2017/2018 and 2018/2019. Running and contact loads

TABLE 1. Age and anthropometric characteristics of U18 and U20 players.

	U18	U20
	Forwards	
N	29	32
Age (y)	17.8 ± 0.5	19.5 ± 0.6
Stature (cm)	187.0 ± 8.2	190.6 ± 6.7
Body mass (kg)	104.2 ± 11.1	110.7 ± 9.6
Match observations	44	68
	Backs	
N	20	24
Age (y)	18.0 ± 0.3	19.5 ± 0.7
Stature (cm)	178.9 ± 4.6	180.7 ± 6.4
Body mass (kg)	82.6 ± 7.9	85.2 ± 6.8
Match observations	28	45

Note: Data are presented as mean ± SD.

were analysed over the whole-match, and specifically during peak match-play phases including short rolling epochs and continuous ball-in-play sequences.

Participants

A total of 105 players participated (U18, *n* = 49; U20, *n* = 56) in the present study. These were split into forward (U18, *n* = 29; U20, *n* = 32) and back positional groups (U18, *n* = 20; U20, *n* = 24). Participants' age and anthropometric characteristics are reported in Table 1.

To ensure player confidentiality, all performance data were anonymized before the analysis. Prior to participation, all the players received comprehensive verbal and written explanations of the study. While data arose as a condition of the players' participation in their respective national teams whereby they underwent daily monitoring during training camps and competition, written informed consent to participate was obtained, with a parent or guardian providing this for all players under 18 years, in conformity with the recommendations of the Declaration of Helsinki. Permission for the study was also obtained from the scientific research board of the French Rugby Federation.

Data collection procedures

Running load

Players wore a portable GPS tracking device (SensorEverywhere V3, Digital Simulation, France), sampling at 16 Hz. The GPS system was placed in a customized pocket in their playing shirt and located between the scapulae. To limit potential inter-unit variability, each player wore the same unit for the entire duration of each competition.

Thirty minutes prior to the start of each match, the GPS units were activated to ensure clear satellite reception. Data were captured and computed using propriety SensorEverywhere Analyser software (Digital Simulation, Paris, France). Data were excluded if one of the following criteria was met: number of satellites < 6, horizontal dilution of precision (HDOP) > 2.3 and visual inspection of raw traces of velocity report irregularities [21]. The mean number of satellites and HDOP during match play were 10 ± 2 and 1.7 ± 0.4 respectively. Recent research assessing the inter-unit reliability of the SensorEverywhere GPS devices demonstrated a trivial difference for typical error of measurement and a small difference for maximal sprinting speed ($0.5 \pm 0.1\%$) and maximal acceleration ($3.9 \pm 0.6\%$) respectively [22].

Contact load

A trained operator coded physical contact-related match actions including tackles, rucks, collisions (when the player carries the ball into the contact), mauls and scrums using video analysis software (SportsCode Elite, Version 10, Hudl, USA). Active participation in a scrum was considered to be from the front row engagement to break up or when the player was seen to be detached following the release of the ball [6]. Backrow players were removed from the scrum coding. Active participation in periods of rucking and mauling was timed from when a player's shoulder entered into contact with the ruck or maul to their detachment from the event [8]. Tackles were considered as actions when a player physically attempted to stop a ball carrier whilst on their feet [8]. Collision events were counted when a physical contact was made between an attacker with a player in the defensive line [23].

The operator also used the video-analysis software to quantify ball-in-play time (effective playing time) as this contextual factor influences time-related changes in running and skill-related match performance in team sports [24]. Contextual variables relating to the matches are presented in Supplementary Table 1.

Data Processing

To synchronize running- and contact-load data, a timestamp marker was created in both GPS and video analysis software at kick-off (when the ball hit the ground). Physical contact-related data was subsequently imported from the Sportcode software into the propriety GPS software.

Three arbitrary running intensity zones were used to adjust running-load data measured in meters (m): total distance (TD), high-speed distance (HSD, velocity > $4 \text{ m} \cdot \text{s}^{-1}$) and very-high speed distance (VHSD, velocity > $7 \text{ m} \cdot \text{s}^{-1}$) [25, 26]. Running load was also assessed using the total number of accelerations performed (actions > $2.5 \text{ m} \cdot \text{s}^{-2}$) [27]. Finally, information on the concomitant number of physical contacts was also provided.

Running-data and contact events were used to determine match demands and compare loads in U18 and U20 players using three approaches:

- 1) Averaged external match load profiles (data were only included if players completed a minimum of one match half).
- 2) Ball-in-play (BIP) sequence analysis: the frequency of occurrence of BIP sequences for durations lasting less than 30 s, between 30 to 60 s, 60 to 90 s, 90 to 120 s, and over 120 s was determined. Concomitant running and contact data for BIP sequences lasting more than 90 s are presented. Data for all the other sequences are provided in the supplementary tables except for very short sequences (< 30 s) which were discarded in order to avoid a skewed representation of intensity [17].
- 3) Peak activity periods: total distance and operator coded contact-events were used singly to define the peak locomotor and contact periods during peak activity periods. A rolling average of 30 s and 1, 2, 3, 4, 5, 6, 8, 10, 12 and 15 min with a step of 1/16 s was used [18].

Statistical Analysis

Data are presented as means $\pm$ standard deviations (SD). A magnitude-based decision approach to the statistical analysis was adopted [28, 29]. Comparisons of U18 and U20 performance and across playing positions were calculated with 90% confidence intervals (90% CI) using specifically designed Excel spreadsheets [30]. Quantitative chances of greater or smaller changes in performance variables were assessed qualitatively and reported as follows: 75–97.5%, likely; 97.5–99%, very likely; > 99%, almost certain [31]. Effect sizes (ES) were quantified to indicate the practical meaningfulness of the differences in mean values. The ES was classified as trivial (< 0.2), small (> 0.2–0.6), moderate (> 0.6–1.2), large (> 1.2–2.0) and very large (> 2.0–4.0) [28]. If the 90% CI overlapped positive and negative values, the magnitude was deemed unclear. The chances that the changes in running or contact load were greater for a group (i.e. greater than the smallest worthwhile change, SWC [0.2 multiplied by the between-subject standard deviation, based on Cohen's d principle], similar or smaller than the other group, were calculated.

RESULTS

General match activity profile

Results (Table 2) show that collectively U18 players covered more TD and HSD and performed more accelerations than U20 peers. The TD and HSD were almost certainly higher in U18 forwards compared with U20 forwards. The VHSD was possibly higher in U18 forwards. Backs belonging to the U18s demonstrated higher values for TD, HSD and accelerations than U20 peers. Unclear differences for VHSD were observed for U18 versus U20 backs. Differences in the frequency of contacts were unclear between U18 and U20 levels irrespective of playing position.

No clear difference was observed for the percentage of effective match playing time between the two age groups.

TABLE 2. Comparisons of running- and contact-loads performance per minute of play between U18 vs U20 players for the team collectively and across back and forward positions.

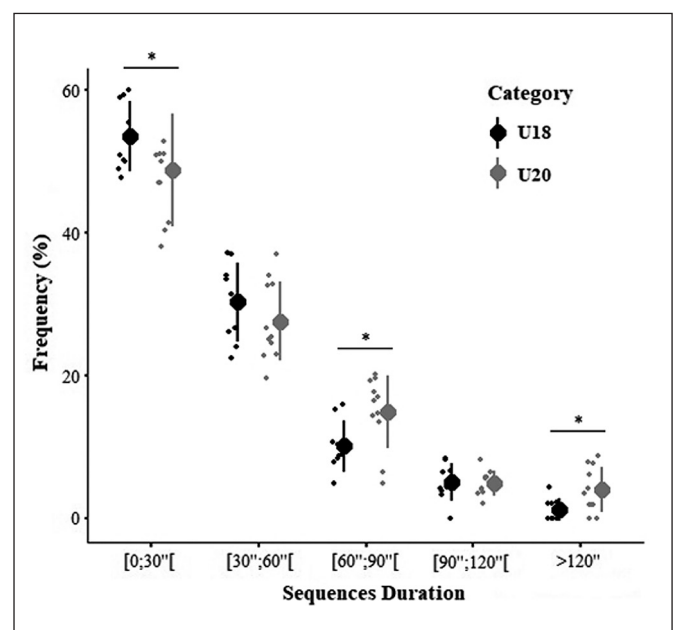
All	U18	U20	%Diff 90%CI	U20 vs U18	
				ES $\pm$ 90%CI	%Chance
% Ball In Play	38.6 $\pm$ 3.2%	38.7 $\pm$ 4.5%	0 $\pm$ 8	0.02 $\pm$ 0.74	34/35/31
TD (m $\cdot$ min ⁻¹)	74.3 $\pm$ 7.5	68.4 $\pm$ 7	-7 $\pm$ 2	-0.76 $\pm$ 0.25	0/0/100
HSD (m $\cdot$ min ⁻¹)	12.0 $\pm$ 5.9	9.3 $\pm$ 4.3	-23 $\pm$ 10	-0.55 $\pm$ 0.25	0/1/99
VHSD (m $\cdot$ min ⁻¹)	0.6 $\pm$ 0.7	0.5 $\pm$ 0.7	-8 $\pm$ 31	-0.07 $\pm$ 0.25	4/77/19
Total Acc (n $\cdot$ min ⁻¹)	0.5 $\pm$ 0.2	0.4 $\pm$ 0.1	-23 $\pm$ 8	-0.71 $\pm$ 0.25	0/0/100
Contact (n $\cdot$ min ⁻¹)	0.4 $\pm$ 0.2	0.4 $\pm$ 0.2	-1 $\pm$ 13	-0.02 $\pm$ 0.25	8/80/12
Forwards					
	U18	U20	%Diff 90%CI	ES $\pm$ 90%CI	%Chance
TD (m $\cdot$ min ⁻¹)	71.6 $\pm$ 5.6	65.4 $\pm$ 4.7	-9 $\pm$ 2	-1.21 $\pm$ 0.32	0/0/100
HSD (m $\cdot$ min ⁻¹)	9.3 $\pm$ 4.4	6.6 $\pm$ 2.6	-29 $\pm$ 12	-0.80 $\pm$ 0.32	0/0/100
VHSD (m $\cdot$ min ⁻¹)	0.3 $\pm$ 0.4	0.2 $\pm$ 0.3	-41 $\pm$ 43	-0.30 $\pm$ 0.32	1/30/69
Total Acc (n $\cdot$ min ⁻¹)	0.4 $\pm$ 0.2	0.3 $\pm$ 0.1	-23 $\pm$ 11	-0.62 $\pm$ 0.32	0/2/98
Contact (n $\cdot$ min ⁻¹)	0.6 $\pm$ 0.2	0.6 $\pm$ 0.1	0 $\pm$ 8	-0.01 $\pm$ 0.32	15/67/18
Backs					
	U18	U20	%Diff 90%CI	ES $\pm$ 90%CI	%Chance
TD (m $\cdot$ min ⁻¹)	78.6 $\pm$ 8.3	74.0 $\pm$ 6.8	-6 $\pm$ 4	-0.62 $\pm$ 0.40	0/5/95
HSD (m $\cdot$ min ⁻¹)	16.3 $\pm$ 5.3	13.4 $\pm$ 2.8	-18 $\pm$ 10	-0.73 $\pm$ 0.40	0/3/97
VHSD (m $\cdot$ min ⁻¹)	1.1 $\pm$ 0.9	1.1 $\pm$ 0.8	2 $\pm$ 30	0.03 $\pm$ 0.40	25/57/18
Total Acc (n $\cdot$ min ⁻¹)	0.6 $\pm$ 0.1	0.4 $\pm$ 0.1	-24 $\pm$ 8	-1.12 $\pm$ 0.40	0/0/100
Contact (n $\cdot$ min ⁻¹)	0.2 $\pm$ 0.1	0.2 $\pm$ 0.1	1 $\pm$ 18	0.03 $\pm$ 0.40	26/56/18

Note: Data are presented as mean $\pm$ SD. Abbreviations: TD, total distance; HSD, high-speed distance; VHSD, very high-speed distance; Total Acc, total accelerations; ES, effect size; CI, confidence interval.

Ball-in-play sequence analysis

In U18s matches, over half of the BIP sequences (Figure 1) lasted less than 30 seconds which was likely more than values observed in U20's competition ($53.5 \pm 4.9\%$ vs $48.8 \pm 7.9\%$, ES = -0.67 ± 0.74). Analysis of longer sequences [60 s;90 s[showed a reversal distribution as likely more sequences were observed in U20 compared to U18 match-play (ES = 1.04 ± 0.74). No differences in the frequency of [90 s;120 s[sequences were observed between age groups. Likely more sequences of > 120 s duration were reported in U20 matches (ES = 1.02 ± 0.74).

Table 3 reports relative running- and contact-loads during BIP sequences of > 90 s duration in U18 versus U20 play. Owing to a low frequency of > 120 s sequences, these were pooled with sequences lasting [90 s;120 s[. Collectively, U18 players performed more TD and HSD than U20 peers during these sequences. U18's backs performed more accelerations than U20s peers, while U20 backs covered more VHSD than U18 backs. U20 forwards performed more contact actions than U18 peers. Outcomes for all other performance variables during > 90 s sequences presented trivial or unclear

**FIG. 1.** Frequency distribution comparison of BIP sequences between U18 vs U20 matches.

Note: *: Likely difference.

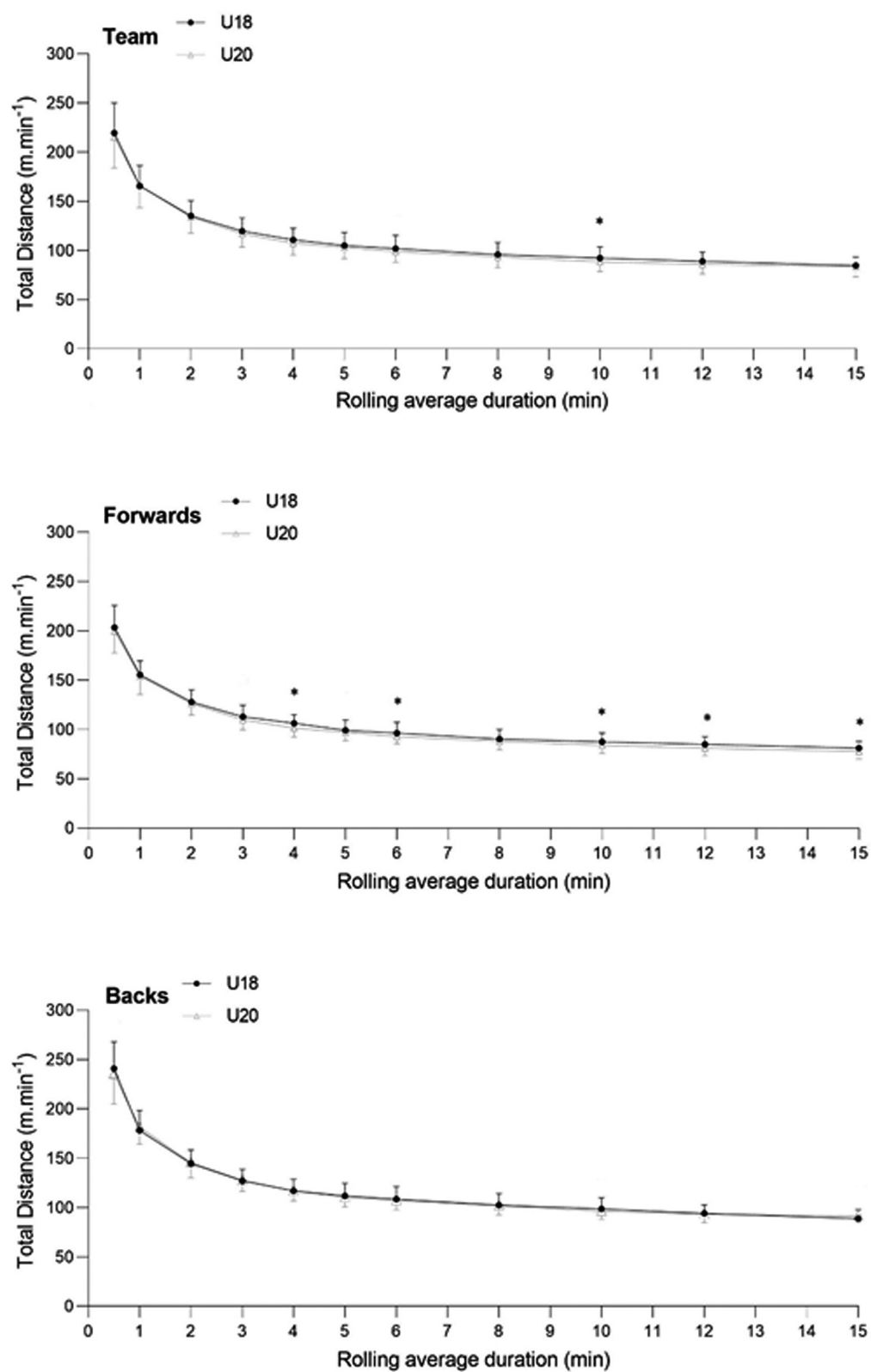


FIG. 2. Comparison of maximal locomotor activity associated with peak TD periods between forwards and backs at U18 and U20 levels. Note: *: Likely difference.

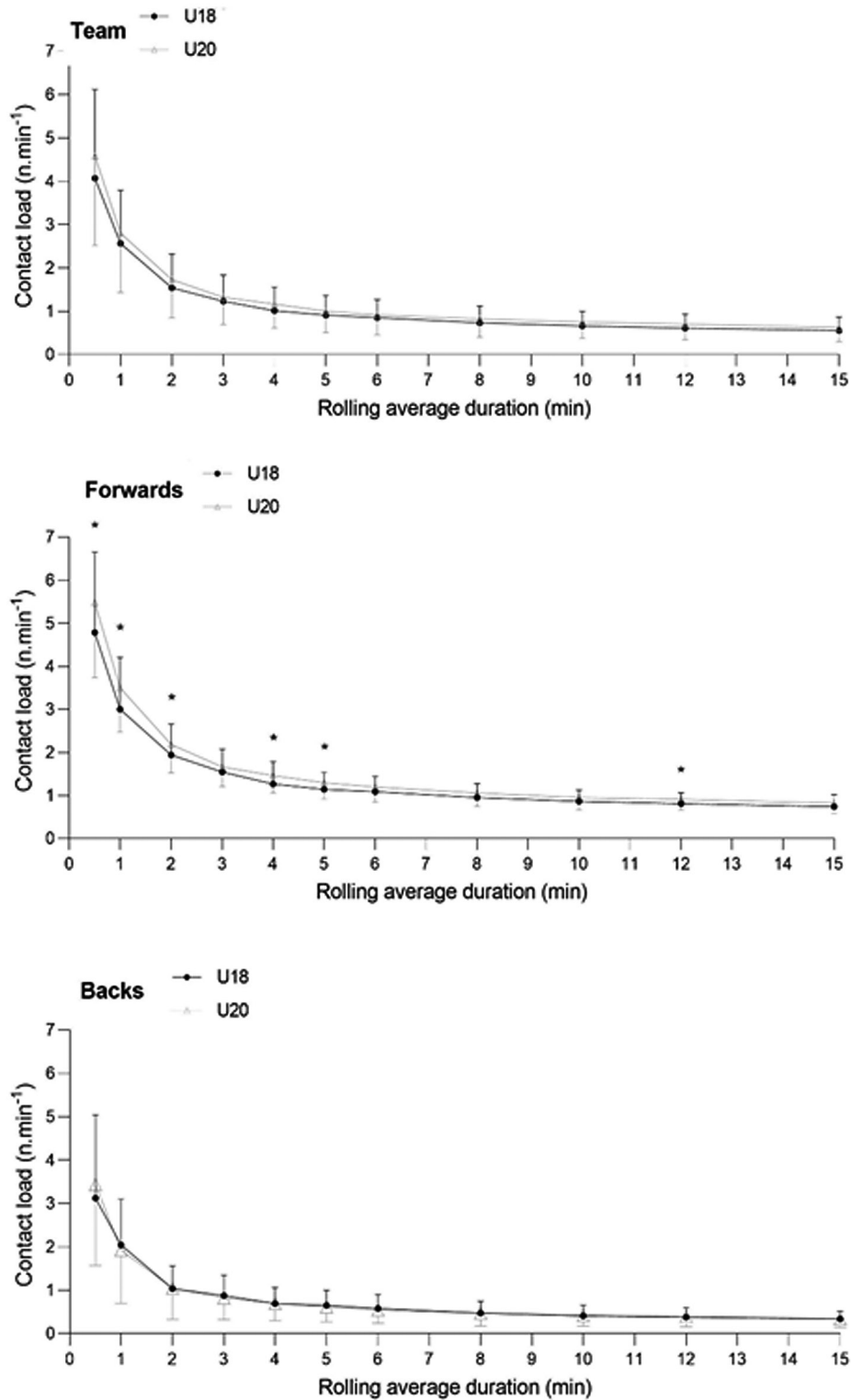


FIG. 3. Comparison of maximal number of contacts associated to peak contact-load periods between forwards and backs at U18 and U20 levels. *: Likely difference.

TABLE 3. Comparisons of running- and contact-loads performance per minute during BIP sequences of > 90 s between U18 vs U20 players for the team collectively and across back and forward positions.

All	U18	U20	%Diff 90%CI	U20 vs U18	
				ES $\pm$ 90%CI	%Chance
Duration (min)	1.8 $\pm$ 0.2	2.1 $\pm$ 0.5	14 $\pm$ 3	0.63 $\pm$ 0.13	100/0/0
TD ($\text{m} \cdot \text{min}^{-1}$)	110.8 $\pm$ 30.7	99.4 $\pm$ 25.5	-10 $\pm$ 3	-0.42 $\pm$ 0.13	0/0/100
HSD ($\text{m} \cdot \text{min}^{-1}$)	24.1 $\pm$ 20.0	17.9 $\pm$ 17.5	-25 $\pm$ 10	-0.33 $\pm$ 0.13	0/5/95
VHSD ($\text{m} \cdot \text{min}^{-1}$)	0.4 $\pm$ 2.0	0.8 $\pm$ 3.8	105 $\pm$ 104	0.13 $\pm$ 0.13	12/88/0
Total Acc ($\text{n} \cdot \text{min}^{-1}$)	0.9 $\pm$ 0.7	0.7 $\pm$ 0.6	-16 $\pm$ 10	-0.20 $\pm$ 0.13	0/48/52
Contact ($\text{n} \cdot \text{min}^{-1}$)	0.9 $\pm$ 0.7	1.0 $\pm$ 0.8	15 $\pm$ 10	0.18 $\pm$ 0.13	38/62/0
Forwards					
Forwards	U18	U20	%Diff 90%CI	U20 vs U18	
				ES $\pm$ 90%CI	%Chance
TD ($\text{m} \cdot \text{min}^{-1}$)	107.8 $\pm$ 26.2	96.0 $\pm$ 22.0	-11 $\pm$ 4	-0.50 $\pm$ 0.17	0/0/100
HSD ($\text{m} \cdot \text{min}^{-1}$)	17.8 $\pm$ 14.3	10.7 $\pm$ 12.0	-40 $\pm$ 12	-0.55 $\pm$ 0.17	0/0/100
VHSD ($\text{m} \cdot \text{min}^{-1}$)	0.4 $\pm$ 2.2	0.1 $\pm$ 1.2	-73 $\pm$ 64	-0.19 $\pm$ 0.16	0/54/46
Total Acc ($\text{n} \cdot \text{min}^{-1}$)	0.8 $\pm$ 0.7	0.7 $\pm$ 0.6	-9 $\pm$ 14	-0.10 $\pm$ 0.17	0/83/17
Contact ($\text{n} \cdot \text{min}^{-1}$)	1.2 $\pm$ 0.7	1.4 $\pm$ 0.7	22 $\pm$ 10	0.35 $\pm$ 0.17	94/6/0
Backs					
Backs	U18	U20	%Diff 90%CI	U20 vs U18	
				ES $\pm$ 90%CI	%Chance
TD ($\text{m} \cdot \text{min}^{-1}$)	115.2 $\pm$ 35.9	103.4 $\pm$ 28.6	-10 $\pm$ 5	-0.38 $\pm$ 0.19	0/8/92
HSD ($\text{m} \cdot \text{min}^{-1}$)	33.2 $\pm$ 23.3	26.3 $\pm$ 19.2	-21 $\pm$ 12	-0.33 $\pm$ 0.19	0/14/86
VHSD ($\text{m} \cdot \text{min}^{-1}$)	0.4 $\pm$ 1.8	1.6 $\pm$ 5.3	316 $\pm$ 222	0.27 $\pm$ 0.19	81/19/0
Total Acc ($\text{n} \cdot \text{min}^{-1}$)	1.0 $\pm$ 0.7	0.8 $\pm$ 0.7	-24 $\pm$ 12	-0.38 $\pm$ 0.19	0/7/93
Contact ($\text{n} \cdot \text{min}^{-1}$)	0.6 $\pm$ 0.6	0.6 $\pm$ 0.5	11 $\pm$ 18	0.12 $\pm$ 0.19	25/75/0

Data are presented as mean $\pm$ SD. Abbreviations: TD, total distance; HSD, high-speed distance; VHSD, very high-speed distance; Total Acc, total accelerations; ES, effect size; CI, confidence interval.

differences. Performance in the other BIP sequences are reported in the supplementary tables.

Analysis of peak activity periods

No difference was observed between the two age groups in running-load during any of the short peak activity periods for the players as a whole (Figure 2). U18 forwards covered likely more total distance (small ES) than U20 forwards in 4, 6, 10, 12 and 15-min peak TD periods. Regarding backs, unclear differences were observed across age groups during peak periods.

U20 forwards performed likely more contact actions (small ES) than U18 forwards during 30 s, 1, 2, 4, 5 and 12-min peak contact load periods (Figure 3) while no differences were observed in U18 versus U20 backs.

DISCUSSION

The aim of this study was to characterize and compare running and contact loads in U18 and U20 international rugby union competition. Key findings were: (1) U18 players covered more TD, HSD and

performed more accelerations per minute compared with U20 peers, (2) a greater frequency of ball-in-play (BIP) sequences of long duration (> 90 s) was observed in U20 versus U18 match-play, while U18s covered slightly more TD and HSD per minute during these > 90 s sequences and, (3) while no clear differences existed between age categories in running performance during short peak periods of activity, a higher frequency of contacts was observed in U20 forwards.

General match activity profile

To our knowledge, this study is the first to report running and contact load characteristics in U18 players in international standard competition and compare with these with data gathered in international U20 peers. The values for running activity observed in both age categories (Table 2), were in the upper range of those reported in previous research on elite standards of play; TD covered per minute ranged from 65 and 74 $\text{m} \cdot \text{min}^{-1}$ for the present U20 forwards and backs respectively vs 62 and 69 $\text{m} \cdot \text{min}^{-1}$ observed in other international U20 players [12]. At elite academy U18 club level [10], TD

values per minute of 71 and 74 $\text{m} \cdot \text{min}^{-1}$ were reported for forwards and backs respectively compared with 72 and 79 $\text{m} \cdot \text{min}^{-1}$ in the present study.

The TD, HSD, and frequency of accelerations were greater in the U18 versus the U20 players. In addition, the VHSD was possibly greater for U18 forwards compared with U20 forwards while an unclear difference was observed between backs. These results tend to confirm trends previously reported across age groups in other elite and sub-elite rugby union populations [9, 11, 12, 32]. Till *et al.* [20] reported higher relative distances covered by U16 county players versus U20 international players. In addition, HSD and the frequency of acceleration actions are greater in U18 games compared with U20 [9, 11, 12]. Taken together, these findings suggest that running activity per se is not a limiting performance criterion in elite and international rugby union, irrespective of playing position, when graduating through different age categories. Owing to comparable TD covered here and data previously reported in a study comparing U20 and senior international players [12], the present findings also support the idea that international U20 competition is an adequate 'stepping stone' for preparing players physically for the overall running demands reported at senior international standards.

In contrast to running activities, no differences regarding the frequency of contact actions were observed across the present age groups, either collectively or for positional role. This result differs to previous findings in county level match-play where a greater frequency of collisions were observed in U16 versus U20 players [9]. This discrepancy across findings could potentially be linked to the French Rugby Federation's national tactical and technical youth technical development performance plan, where a similar and consistent training plan is implemented across age groups. Similar research is nevertheless warranted in other international populations to verify whether these contact demands reflect those observed at senior standards. Moreover, we can suppose that as body mass increases with age, the magnitude of contact increases although research is necessary to confirm this suggestion.

Ball-in-play sequences

To our knowledge, this study is also the first to quantify the frequency of occurrence of BIP game sequences and associated physical outputs in U18 and U20 international rugby union players. Similar to Read *et al.*'s [19] findings showed in U18s competition, over half of BIP sequences observed were of < 30 s duration. In contrast, U20s completed a moderately greater number of longer sequences (60–90; and > 120 s). While complementary research using video- and match-analyses is necessary, a reasonable explanation for this difference could be linked to a greater technical and tactical ability in U20 players enabling them to collectively conserve ball possession over longer periods [9].

Regarding the concomitant physical characteristics observed during sequences of play of > 90 s in duration (Table 3), U18s covered

almost certainly more relative TD and likely more HSR compared to U20 peers. It is also noteworthy that the TD covered by the present U18s was higher than values observed in senior international rugby union match-play during sequences of the same duration [17]. These results once again tend to imply that running activity per se is not a discriminant factor when progressing through U18 and U20 international age categories and that match demands at younger levels provide adequate opportunities to prepare players for senior international rugby.

While U18s as a whole performed more relative TD during longer playing sequences, contrasting high-intensity demands were apparent across positional groups within the two age groups. The frequency of contact events during these long sequences was approximately 20% higher (small ES) in forwards in U20's versus U18's match-play while U20 backs covered more VHSD (small ES) compared to U18s peers. These results suggested that at U20 standards, greater emphasis could be placed on developing position-specific physical skills, through adapted physical conditioning programmes to respond to the high intensity demands occurring in longer sequences of play that occur frequently in this age category.

Peak Activity Periods

The analysis of collective peak running-load activity (distance run per minute) reported no differences between the two age groups during any of the peak activity periods (Figure 2). The positional group demands observed during a 2-min maximal running activity window showed that performance was not dissimilar to that previously reported in forwards at U18 English academy level [18]. During a 2-min maximal window, English academy forwards covered distances ranging from 121 to 132 $\text{m} \cdot \text{min}^{-1}$ compared to 128 and 126 $\text{m} \cdot \text{min}^{-1}$ in the present U18 forwards and U20 forwards, respectively. In contrast, English academy U18 backs in the same study tended to cover lower distances than the present international U18 backs during a 2-min peak activity period (range: 133 to 146 $\text{m} \cdot \text{min}^{-1}$ versus 144 and 145 $\text{m} \cdot \text{min}^{-1}$ for the present U18 backs and U20 backs respectively). In comparison to international senior standards, the current results across both positional groups and age categories were comparable for short periods of peak activity (from 1-min to 5-min) [15, 16]. During longer peak activity periods (> 10-min) the present younger players completed greater relative distances than senior international players [16]. To summarize, peak TD distance activity in U18 and U20 match-play were higher than in peers in elite academies yet tended to be stable across these age categories. Performance was also comparable to that observed in senior international players suggesting that younger international players would be able to respond physically to the running demands observed at the very highest standards of the game.

The peak period running data reported above has potential for application in designing training prescriptions based upon 'worse-case' scenarios for physical conditioning sessions [15]. Similarly, contact

activity during peak periods also provides practitioners with information on contact loading for prescription and monitoring of physical contact training sessions (Figure 3). While no collective differences were observed between the U18 and U20 categories, U20 forwards performed likely more contact actions than U18 peers during short peak periods lasting less than 4-min in duration (ES range from 0.36 to 0.46). These results suggest that when U18's graduate to U20 level, there is a need to adapt the training contact dose to enhance their capacity to repeat contact events.

Limitations

In the current study, only the frequency of contact events was quantified, and future research is warranted to determine the intensity of these events (quantified in G) notably using the accelerometer and gyroscope technologies housed within the GPS. As such, this would enable a more precise evaluation of contact demands between the two age groups as one would expect that contact intensity is greater in U20 competition owing to the larger body mass of U20 players [33, 34]. Additional match analysis research is required to determine the concomitant collective and position-specific tactical and technical demands and peak phases to provide a more holistic understanding of match performance. It is also possible that the national playing style guidelines specific to France's national youth team development program biased the present findings. Accordingly, additional studies ideally using larger sample sizes (matches and players) and data gathered in populations from other nations are necessary [35].

CONCLUSIONS

To our knowledge, this study is the first to characterize and compare locomotor and contact loads in international U18 and U20 rugby

match-play. It appears that the demands observed at U18 level suffice to help prepare players physically for U20 levels while demands in the latter are comparable to those previously reported in senior international match-play. Future work should focus on determining the concomitant technical and/or tactical aspects of play to provide a more holistic understanding of match performance demands at younger levels.

Practical applications

- The activity profiles observed in international U18 match-play suggest that players in this age group are sufficiently well-prepared physically for the general running and contact loads and those specific to ball-in-play sequences observed at U20 standards.
- The present information on maximal running intensities can inform running loads for high-intensity conditioning sessions and small-sided games in younger elite players.
- These results can also aid practitioners to manage and individualize contact loads across age categories and positional groups during high-intensity training drills.

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Conflict of interest declaration

The authors declare no conflict of interest.

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SUPPLEMENTARY TABLE 1. Contextual variables of matches investigated.

	U18	U20
Win (n) / Loose (n)	8 / 1	8 / 3
Victory % / Loose %	89% / 11%	73% / 27%
Opponent possession %	51.5 ± 7.4	49.4 ± 8.4
France possession %	48.5 ± 7.4	50.6 ± 8.4
Total number of tries	7.2 ± 2.2	7.4 ± 4.2
Opponent number of tries	2.6 ± 1.2	2.7 ± 2.5
France number of tries	4.7 ± 1.7	4.6 ± 3.5
Total number of points	51.9 ± 12.8	56.9 ± 23.2
Opponent number of points	20 ± 7.4	21.5 ± 14.8
France number of points	31.9 ± 8.1	35.4 ± 22.1

Note: Data are presented as mean ± SD.

SUPPLEMENTARY TABLE 2. Comparisons of running- and contact-loads performance per minute during BIP sequences lasting 30 s to 60 s between U18 vs U20 players for the team collectively and across back and forward positions.

All	U18	U20	Diff% 90%CI	U20 vs U18	
				ES ± 90%CI	%Chance
Duration (min)	0.7 ± 0.1	0.7 ± 0.1	2 ± 1	0.08 ± 0.06	0/100/0
TD (m·min ⁻¹)	115.0 ± 36.1	101.5 ± 36.5	-12 ± 2	-0.37 ± 0.06	0/0/100
HSD (m·min ⁻¹)	31.4 ± 32.4	21.6 ± 27	-31 ± 6	-0.33 ± 0.06	0/0/100
VHSD (m·min ⁻¹)	1.9 ± 8.4	1.1 ± 5.6	-42 ± 22	-0.11 ± 0.06	0/99/1
Total Acc (n·min ⁻¹)	1.0 ± 1.2	0.9 ± 1.1	-12 ± 6	-0.11 ± 0.06	0/99/1
Contact (n·min ⁻¹)	0.6 ± 1	0.8 ± 1	36 ± 10	0.22 ± 0.06	70/30/0
Forwards	U18	U20	Diff% 90%CI	U20 vs U18	
				ES 90%CI	%Chance
TD (m·min ⁻¹)	112.2 ± 32.4	98.7 ± 32.8	-12 ± 2	-0.41 ± 0.08	0/0/100
HSD (m·min ⁻¹)	24.7 ± 27.4	15.4 ± 21.6	-38 ± 8	-0.38 ± 0.08	0/0/100
VHSD (m·min ⁻¹)	0.6 ± 4.4	0.2 ± 2.2	-67 ± 46	-0.12 ± 0.08	0/95/5
Total Acc (n·min ⁻¹)	0.9 ± 1.1	0.8 ± 1	-14 ± 9	-0.11 ± 0.08	0/96/4
Contact (n·min ⁻¹)	0.8 ± 1.1	1.2 ± 1.1	45 ± 11	0.32 ± 0.08	99/1/0
Backs	U18	U20	Diff% 90%CI	U20 vs U18	
				ES 90%CI	%Chance
TD (m·min ⁻¹)	119.0 ± 40.5	104.8 ± 40.2	-12 ± 3	-0.35 ± 0.09	0/0/100
HSD (m·min ⁻¹)	41.1 ± 36.3	29.0 ± 30.7	-30 ± 7	-0.37 ± 0.09	0/0/100
VHSD (m·min ⁻¹)	3.7 ± 11.7	2.1 ± 7.7	-43 ± 23	-0.17 ± 0.09	0/71/29
Total Acc (n·min ⁻¹)	1.2 ± 1.2	1.1 ± 1.2	-13 ± 9	-0.13 ± 0.09	0/88/12
Contact (n·min ⁻¹)	0.4 ± 0.7	0.5 ± 0.8	30 ± 19	0.15 ± 0.09	16/84/0

Note: Data are presented as mean ± SD. Abbreviations: TD, total distance; HSD, high-speed distance; VHSD, very high-speed distance; Total Acc, total accelerations; ES, effect size; CI, confidence interval.

SUPPLEMENTARY TABLE 3. Comparisons of running- and contact-loads performance per minute during BIP sequences lasting 60 s to 90 s between U18 vs U20 players for the team collectively and across back and forward positions.

All	U18	U20	Diff% 90%CI	U20 vs U18	
				ES $\pm$ 90%CI	%Chance
Duration (min)	1.2 $\pm$ 0.1	1.2 $\pm$ 0.1	-2 $\pm$ 1	-0.16 $\pm$ 0.09	0/75/25
TD (m $\cdot$ min ⁻¹)	107.6 $\pm$ 31.4	101.7 $\pm$ 31.6	-5 $\pm$ 3	-0.18 $\pm$ 0.09	0/60/40
HSD (m $\cdot$ min ⁻¹)	23.4 $\pm$ 21.7	21.0 $\pm$ 21.0	-11 $\pm$ 9	-0.12 $\pm$ 0.09	0/93/7
VHSD (m $\cdot$ min ⁻¹)	0.9 $\pm$ 3.6	0.9 $\pm$ 3.8	-7 $\pm$ 38	-0.02 $\pm$ 0.09	0/100/0
Total Acc (n $\cdot$ min ⁻¹)	0.9 $\pm$ 0.9	0.8 $\pm$ 0.8	-15 $\pm$ 9	-0.16 $\pm$ 0.09	0/72/28
Contact (n $\cdot$ min ⁻¹)	0.8 $\pm$ 0.9	1 $\pm$ 0.9	21 $\pm$ 10	0.19 $\pm$ 0.09	43/57/0
Forwards	U18	U20	Diff% 90%CI	U20 vs U18	
				ES 90%CI	%Chance
TD (m $\cdot$ min ⁻¹)	105.5 $\pm$ 28.3	98.9 $\pm$ 26.4	-6 $\pm$ 3	-0.25 $\pm$ 0.12	0/27/73
HSD (m $\cdot$ min ⁻¹)	18.3 $\pm$ 17.2	14.8 $\pm$ 15.2	-19 $\pm$ 11	-0.22 $\pm$ 0.12	0/40/60
VHSD (m $\cdot$ min ⁻¹)	0.4 $\pm$ 2.1	0.2 $\pm$ 1.9	-40 $\pm$ 69	-0.07 $\pm$ 0.12	0/95/5
Total Acc (n $\cdot$ min ⁻¹)	0.9 $\pm$ 0.9	0.7 $\pm$ 0.8	-20 $\pm$ 12	-0.21 $\pm$ 0.12	0/45/55
Contact (n $\cdot$ min ⁻¹)	1.1 $\pm$ 0.9	1.4 $\pm$ 0.9	27 $\pm$ 11	0.32 $\pm$ 0.12	94/6/0
Backs	U18	U20	Diff% 90%CI	U20 vs U18	
				ES 90%CI	%Chance
TD (m $\cdot$ min ⁻¹)	110.4 $\pm$ 35.1	105.3 $\pm$ 36.7	-5 $\pm$ 5	-0.14 $\pm$ 0.14	0/75/25
HSD (m $\cdot$ min ⁻¹)	30.8 $\pm$ 25.1	28.6 $\pm$ 24.4	-7 $\pm$ 12	-0.09 $\pm$ 0.14	0/90/10
VHSD (m $\cdot$ min ⁻¹)	1.7 $\pm$ 5	1.6 $\pm$ 5.1	-4 $\pm$ 43	-0.01 $\pm$ 0.14	1/98/2
Total Acc (n $\cdot$ min ⁻¹)	1.0 $\pm$ 0.9	0.9 $\pm$ 0.9	-11 $\pm$ 13	-0.13 $\pm$ 0.14	0/80/20
Contact (n $\cdot$ min ⁻¹)	0.5 $\pm$ 0.7	0.5 $\pm$ 0.6	13 $\pm$ 19	0.10 $\pm$ 0.14	14/86/0

Note: Data are presented as mean $\pm$ SD. Abbreviations: TD, total distance; HSD, high-speed distance; VHSD, very high-speed distance; Total Acc, total accelerations; ES, effect size; CI, confidence interval.

A novel application of entropy analysis for assessing changes in movement variability during cumulative tackles in young elite rugby league players

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ABSTRACT: The aim of this study was to identify between-position (forwards vs. backs) differences in movement variability in cumulative tackle events training during both attacking and defensive roles. Eleven elite adolescent male rugby league players volunteered to participate in this study (mean $\pm$ SD, age; 18.5 $\pm$ 0.5 years, height; 179.5 $\pm$ 5.0 cm, body mass; 88.3 $\pm$ 13.0 kg). Participants performed a drill encompassing four blocks of six *tackling* (i.e. tackling an opponent) and six *tackled* (i.e. being tackled by an opponent while carrying a ball) events (i.e. 48 total tackles) while wearing a micro-technological inertial measurement unit (WIMU, Realtrack Systems, Spain). The acceleration data were used to calculate sample entropy (SampEn) to analyse the movement variability during tackles performance. In tackling actions SampEn showed significant between-position differences in block 1 ($p = 0.0001$) and block 2 ($p = 0.0003$). Significant between-block differences were observed in backs (block 1 vs 3, $p = 0.0021$; and block 1 vs 4, $p = 0.0001$) but not in forwards. When being tackled, SampEn showed significant between-position differences in block 1 ($p = 0.0007$) and block 3 ($p = 0.0118$). Significant between-block differences were only observed for backs in block 1 vs 4 ($p = 0.0025$). Movement variability shows a progressive reduction with cumulative tackle events, especially in backs and when in the defensive role (tackling). Forwards present lower movement variability values in all blocks, particularly in the first block, both in the attacking and defensive role. Entropy measures can be used by practitioners as an alternative tool to analyse the temporal structure of variability of tackle actions and quantify the load of these actions according to playing position.

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INTRODUCTION

Rugby league are physically demanding team sports characterised by a high frequency of tackle events [1]. As such, tackles result in considerable increases in total energy expenditure [2] and upper-body neuromuscular and perceptual fatigue [3]. Furthermore, tackles require high levels of physical fitness and a set of coordinated movement patterns [4]. Consequently, developing tackle and contact abilities

becomes an essential aspect of training prescription in the rugby codes [4]. Tackle actions are performed during both defensive and attacking phases of play [5], but defensive tackling may prove crucial in determining the match outcome if they are able to prevent the attacking team progressing towards their try line and scoring a try [6–8]. Therefore, it is important that defensive players are able

to maintain the intensity and technique during defensive tackles. Tackle characteristics are different between playing positions, with forwards being involved in more tackles than backs during a match, with the highest frequency recorded for hit-up forwards group (i.e., 35 to 48) compared to the outside backs group (i.e., 23 to 32) [9–11]. Thus, players have different collision-profiles and require different collision training to adequately prepare for the physical-technical characteristics of competitions [12–14].

To adequately prepare for the physical-technical characteristics of competitions, microtechnology is used to study match demands to inform training. Research on the use of microtechnology to quantify external loads in team sports has grown exponentially in the last years [3, 15, 16]. However, most of the research has focused on global positioning system (GPS) derived variables (e.g. distance, high-speed running, accelerations, and decelerations), with limited focus on collisions (e.g., the tackle) [17]. Some micro-technology devices contain multiple components such as accelerometers or gyroscopes, which may provide valuable information related to human movement, with application to the tackle [17]. For instance, accelerometer-derived metrics can be used to quantify the number and magnitude of collision events [12, 15, 16]. In the existing literature, tackle analyses have typically quantified the magnitude of these events and potential changes in technique [4, 6, 12, 18]. Also, the most demanding passages of rugby league match-play involve cumulative tackles and collisions with short recovery between efforts [19]. At the elite level, rugby league players can often be exposed to between 29 and 74 collisions (i.e., tackles and carries) per game [11, 19], or to more than 3 collisions per minute [20]. As such, cumulative tackles events may deteriorate tackle technique and efficiency over time by affecting its movement variability, especially when a player is required to make repeated tackles with their non-dominant side [21, 22], although to date limited research exists in this area.

Movement variability can be defined as a certain amount of change during athletic performance (e.g. a tackle) and perceived as a key element for identifying the amount of perturbation (incidents that change a system state from a stable to an unstable situation or vice versa) in a specific sporting action [23–25]. Therefore, human movement variability can provide an additional tool for quantifying the tackle demands of team sports. Human movement analysis has evolved to assess the variability of a measure by targeting the detection of changes in fluctuations and spatiotemporal characteristics of its outcomes. Linear analyses of human movement have several recognised limitations, mainly in determining the degree of complexity and the time-dependent structure of a time series [26]. These limitations can be complemented by using non-linear analyses, such as measures of entropy. The advantages on this method lie in the additional information on the way in which the levels of a biological system are related, and the organization of athlete's movement from a dynamical system perspective [27]. Currently, the most commonly used methods for biological data are approximate entropy (ApEn)

and, more recently, sample entropy (SampEn) and multiscale entropy (MSE) [27–32]. All of them, are mathematical algorithms to quantify the amount of regularity and the unpredictability of fluctuations over time-series data. However, they can be considered particularly appropriate for the study of sports movements, although it appears that SampEn is more reliable for short data sets [33]. SampEn measures the probability that similar sequences of points in the time-series remain similar within a tolerance level when a point is added to the sequence, in a single time scale [34]. Furthermore, entropy provides researchers the ability to quantify complexity setting high regularity as low entropy and a very random movement as high entropy. Within the past 20 years, entropy analysis has gained popularity in movement sciences in sports to describe changes in postural control [35–38], assessment of running [39, 40], human walking data [41–43], tactical behaviour in soccer [44, 45], force production [46–48] and as a measure of system complexity in sports [49]. Recently, it has also been validated for detecting increases in movement variability in elite rugby players during resistance training when a ball is included [50, 51].

To our knowledge, no study has explored the movement variability in tackle actions and its changes during repeated tackles. Therefore, the aim of this study was to identify between-position (forwards vs. backs) differences in movement variability in cumulative tackles events training during both attacking and defensive roles.

MATERIALS AND METHODS

Subjects

Eleven elite adolescent male rugby league players (mean $\pm$ SD, age; 18.5 ± 0.5 years, height; 179.5 ± 5.0 cm, body mass; 88.3 ± 13.0 kg) were recruited for this study, six forwards and five backs. All participants were selected from a single professional rugby league academy based in England. Prior to volunteering, the experimental protocol was explained to all participants both verbally and in writing, with a written statement of consent signed (in the case of minors, players provided assent and parents provided consent). The procedures complied with the Declaration of Helsinki (2013) and were approved by Leeds Beckett University Research Ethics Committee.

Design and Methodology

Participants performed a drill encompassing 48 one-on-one tackles divided into 24 *tackling* (i.e. tackling an opponent) and 24 *tackled* (i.e. being tackled by an opponent while carrying a ball) events. These drills were structured in four blocks, and each block consisted of six *tackling* and six *tackled* activities in random order. The players started in front of each other, when the coach marked the start, the players crossed two meters in the opposite direction and then changed direction to execute the tackle at the central point (Fig. 1). The players were divided by positions (e.g., forwards or backs), so that they were always paired with a player of their same position. The experimental protocol began with a standardised 10-minute warm-up.

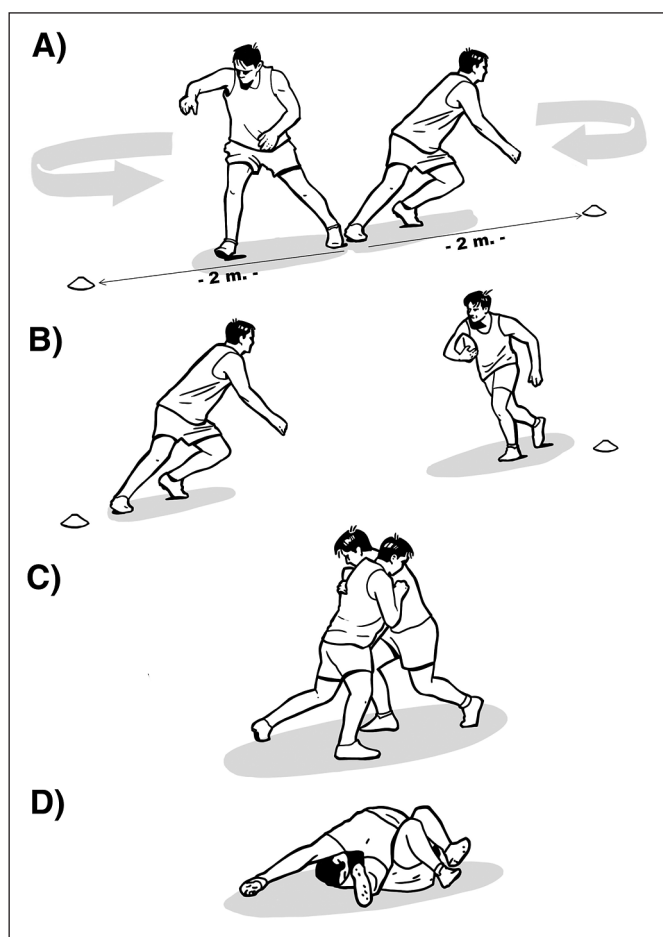


FIG. 1. One-on-one tackles. Players started in front of each other, when the coach marked the start the players crossed two meters in the opposite direction (A) and then changed direction (B) to execute the tackle at the central point (C, D).

Participants were instructed and encouraged to tackle with maximum effort. During *tackling* actions, participants alternated between shoulders (i.e. three tackles using the dominant shoulder and three tackles using the non-dominants shoulder) within each block. Ninety seconds of passive recovery was prescribed between each block. Professional coaches directed the sessions to ensure session safety and ecological validity. The prescribed 48 collisions account for more than the match demands reported for professional rugby league [52] and rugby union [53], to induce a greater level of tackle induced fatigue. A total of 528 tackles were analysed (288 for forwards and 240 for backs).

Participants wore a micro-technology inertial measurement unit (WIMU, Realtrack Systems, Almeria, Spain), which was tightly fitted to the athletes upper back with a specialised vest to minimise incidental unit movement and enhance reliability [17]. The micro-technology units contain a 10 Hz Galileo GPS positioning device, a 3D accelerometer; 100G recording at 1000 Hz, a 3D gyroscope

recording at 1000 Hz. The devices were calibrated prior to their placement. This was done with a self-calibration system that incorporates each device in the internal configuration of the boot. During self-calibration, three aspects were taken into account: (i) leaving the device immobile for 30 s; (ii) placing it in a flat area; and (iii) no magnetic devices around it [54]. These devices have reported good results in accuracy and reliability of his different sensors in previous studies [54–58].

The raw acceleration signal was extracted from each device (from fig 1B to 1D), and processed using a summation of vectors (AcelT) in three axes, mediolateral (x), anteroposterior (y) and vertical (z) calculated according to Gómez-Carmona et al. (2018) [56]. AcelT indicates only the acceleration, in g-force values, recorded by the 3D accelerometers that make up the inertial device with a sample frequency of 1000 Hz, all without the application of a calculation to modify the raw data from the signal. Therefore, if accelerometers recorded the AcelT variable in a reliable form, all variables calculated using accelerometers would be reliable [56]. To obtain a clean acceleration signal, an optimum filter process related to the different sample frequencies was applied [56].

Two of the most widely used and successful entropy estimators are Approximate Entropy (ApEn) and Sample Entropy (SampEn) [31]. ApEn quantifies the similarity probability of patterns of length m and $m + 1$. SampEn is a similar statistic, and it also measures the probability of subsequences being close at two lengths m and $m + 1$. However, SampEn does not include self-comparisons and exhibits greater consistency than ApEn [31]. For this reason, we used SampEn for the current study. Mathematical equation of SampEn is [34, 59]:

1) Form m -vectors, $X(1)$ to $X(N-m+1)$ defined by:

$$X(i) = [x(i), x(i+1), \dots, x(i+m-1)] \quad i = 1, N-m+1 \quad (1)$$

2) Define for each i , for $i = 1, N-m$, let

$$B_i^m(r) = \frac{1}{N-m+1} \times \text{no. of } d_m[X(i), X(j)] \leq r, \quad i \neq j \quad (2)$$

3) Similarly, define for each i , for $i = 1, N-m$, let

$$A_i^m(r) = \frac{1}{N-m+1} \times \text{no. of } d_{m+1}[X(i), X(j)] \leq r, \quad i \neq j \quad (3)$$

4) After define:

$$B^m(r) = \frac{1}{N-m} \sum_{i=1}^{N-m} B_i^m(r) \quad (4)$$

$$A^m(r) = \frac{1}{N-m} \sum_{i=1}^{N-m} A_i^m(r) \quad (5)$$

5) Finally:

$$\text{SampEn}(m, r, N) = -\ln \left(\frac{A^m(r)}{B^m(r)} \right) \quad (6)$$

The (AcelT) signal was cut separating each collision, obtaining 48 signals for each subject and device. Sample entropy (SampEn) for each signal were calculated. Entropy was done according to Goldberger *et al.* [60] and through dedicated routines programmed in Matlab®(The MathWorks, Massachusetts, USA). We used the template length m of 2, and the tolerance criterion of 0.20 in the analyses.

Statistical Analysis

Descriptive analyses are reported as mean $\pm$ standard deviations. Data normality and homogeneity was assessed using Shapiro-Wilk and Levene tests, respectively. Data analyses were conducted using PASW Statistics 21 (SPSS, Inc., Chicago, IL, USA). Independent sample T-tests were used to evaluate differences in SampEn between positions in each block, one for attacking and other for defensive roles. Four linear mixed-effects models were used to model the main and interactive effects between blocks for dependent variables

TABLE 1. Means ($\pm$ SD) of Sample Entropy values between-position (forwards vs. backs) during both attacking and defensive role.

		Backs	Forwards
Block 1	Tackling	0.085 ± 0.012	0.067 ± 0.013
	Tackled	0.085 ± 0.010	0.069 ± 0.014
Block 2	Tackling	0.079 ± 0.006	0.066 ± 0.008
	Tackled	0.077 ± 0.011	0.073 ± 0.011
Block 3	Tackling	0.072 ± 0.008	0.066 ± 0.007
	Tackled	0.081 ± 0.006	0.069 ± 0.009
Block 4	Tackling	0.069 ± 0.008	0.063 ± 0.006
	Tackled	0.071 ± 0.011	0.065 ± 0.014

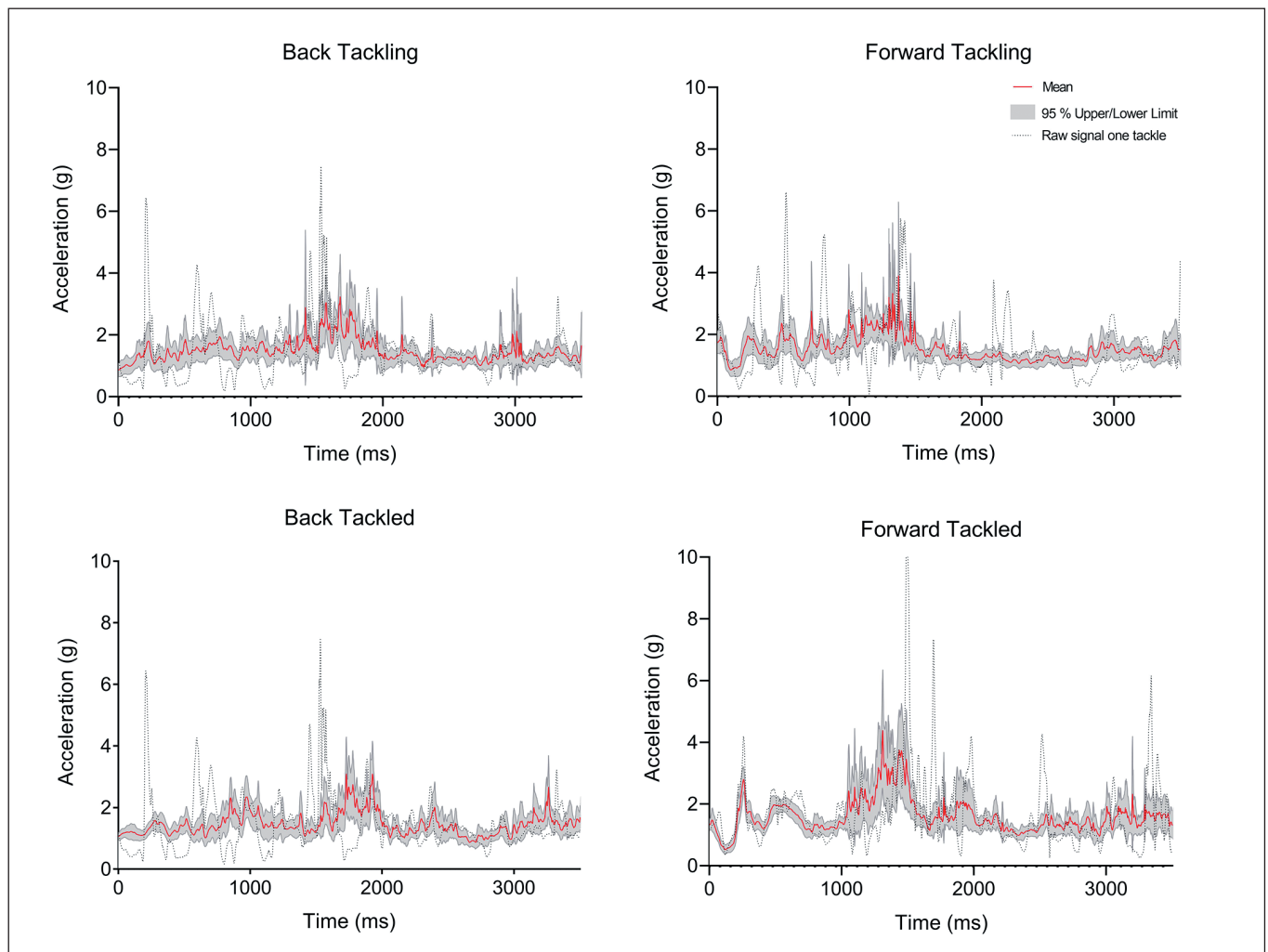


FIG. 2. Raw data of acceleration signal of one tackle, mean over blocks and 95% confidence interval for one player in each condition. Back tackling, back tackled, forward tackling and forward tackled.

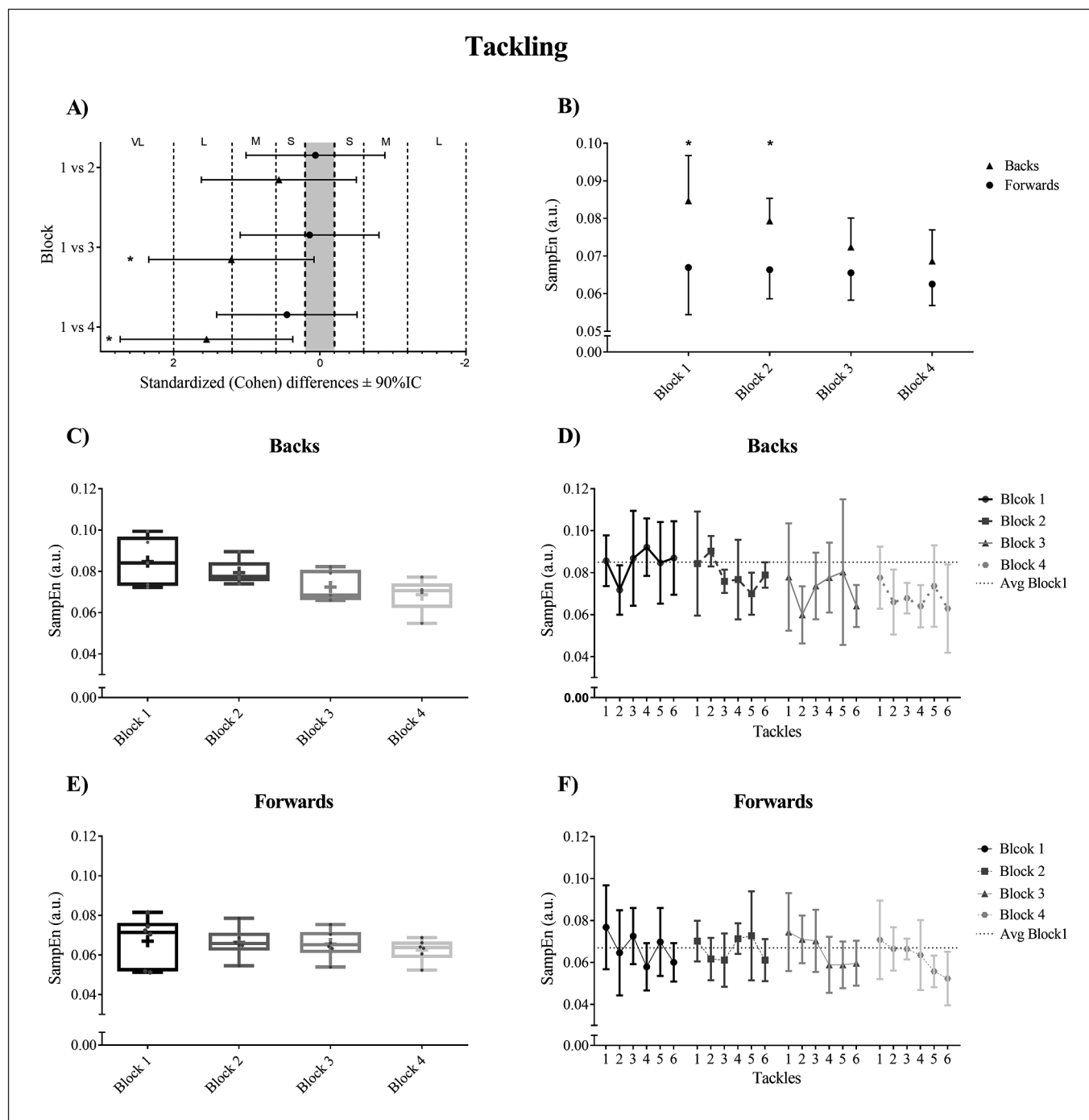


FIG. 3. Movement variability when tackling for backs and forwards. (A). Standardised Cohen's differences between blocks. Error bars indicate uncertainty in true mean changes with 90% confidence intervals. VL: Very Large; L: Large; M: Moderate; S: Small. (B). SampEn (mean $\pm$ SD) and T-test analysis between positions within each block. (C, E). Box-and-Whisker-Plots in each block for backs and forwards respectively. (D, F). Average and standard deviation in all defensive tackles for backs and forwards respectively. The significant differences were shown as * $p < 0.05$.

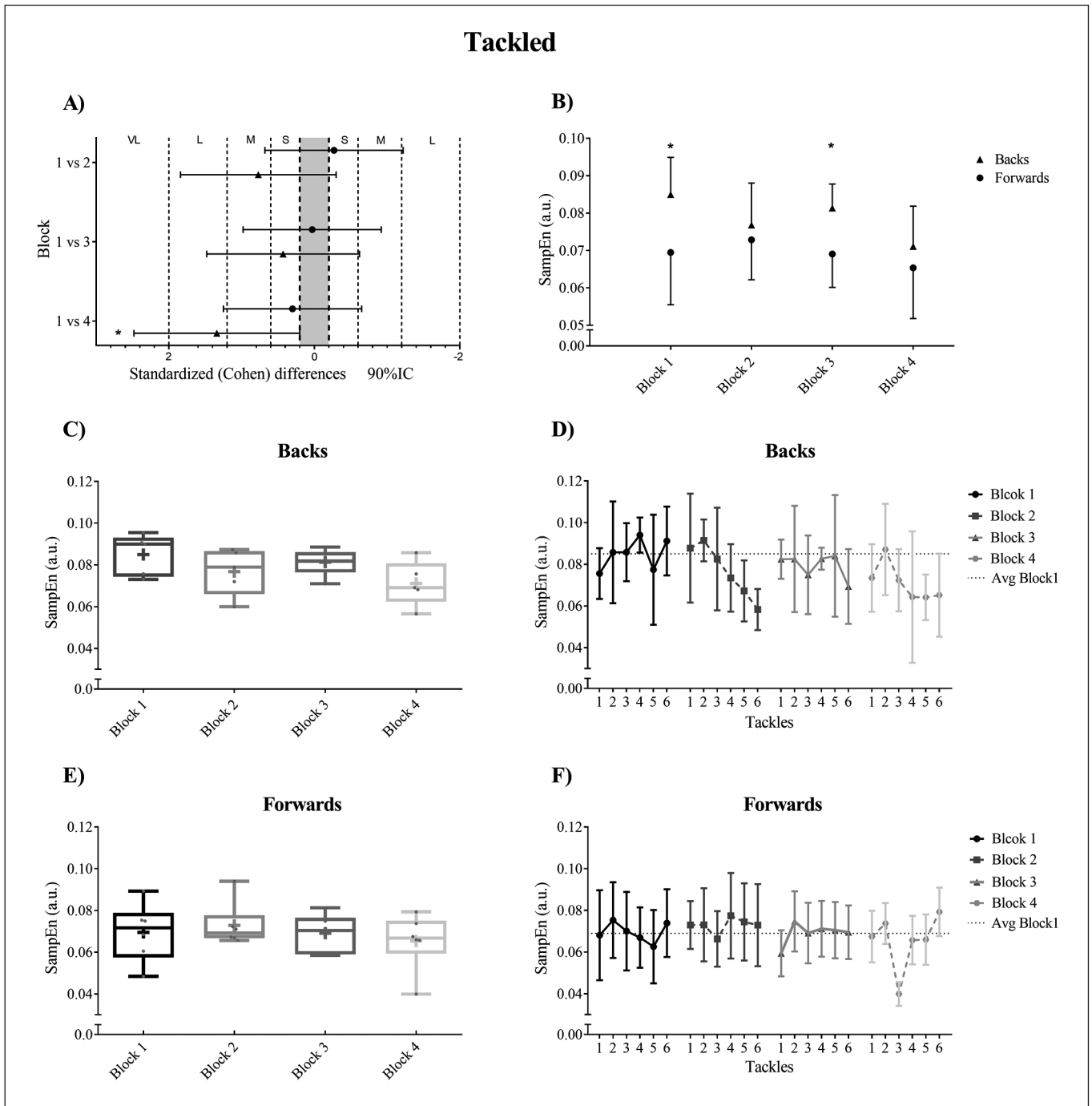


FIG. 4. Movement variability when being tackled for backs and forwards. (A). Standardised Cohen's differences between blocks. Error bars indicate uncertainty in true mean changes with 90% confidence intervals. VL: Very Large; L: Large; M: Moderate; S: Small. (B). SampEn (mean $\pm$ SD) and T-test analysis between positions within each block. (C, E). Box and whisker plots in each block for backs and forwards respectively. (D, F). Average and standard deviation in all attacking tackles for backs and forwards respectively. The significant differences were shown as * $p < 0.05$.

(SampEn) divided between-position and attacking and defensive role (forwards attacking, forwards defensive, backs attacking and backs defensive). The 'ID' of the player was treated as the fixed effect, whereas the random effect was 'block' for all analyses.

The comparisons were also assessed via standardised mean differences (Cohen's *d*) and respective 90% confidence intervals. Thresholds for effect sizes statistics were < 0.20, trivial; 0.20–0.59, small; 0.6–1.19, moderate; 1.20–1.99, large; and > 2.0, very large [61]. For all statistical tests, a *p* < 0.05 was considered statistically significant.

Within-block acceleration variability was analysed using coefficient of variation expressed as a percentage of the mean acceleration signal (CV%) and was represented using box and whisker plots. The box and whisker plots display the first and third quartiles as the ends of the box, the maximum and minimum as the whiskers and the median and average as a vertical bar and + symbol respectively in the interior of each box.

RESULTS

The average and standard deviation of SampEn values for tackling and tackled for forwards and backs in each block are shown in Table 1. Moreover, raw data (acceleration signal) of one tackle are shown as example in figure 2.

Tackling:

The duration of tackling in milliseconds (mean ± SD) was 3775.42 ± 312.88 ms for forwards and 3863.47 ± 403.21 ms for backs. Figure 3 shows movement variability when tackling for backs and forwards. Standardised mean differences (Cohen's *d*) and linear mixed-effects model with interactive effects between blocks for dependent variables (SampEn) divided into two positional groups (backs and forwards) for *tackling* is shown in Figure 3A. In backs, significant differences were observed in block 1 vs 3 (*p* = 0.0021) (ES = -0.560) and in block 1 vs 4 (*p* = 0.0001) (ES = -1.550), but not in block 1 vs 2 (*p* = 0.2002) (ES = -1.210). No significant differences were observed in any of the studied block comparisons in forwards (block 1 vs 2, *p* = 0.8290, ES = -0.060; block 1 vs 3, *p* = 0.6102, ES = -0.140; block 1 vs 4, *p* = 0.1155, ES = -0.450). Figure 3B shows SampEn (mean ± SD) and T-test analysis for differences between positions within each block. Significant between-position differences were observed in block 1 (*p* = 0.0001) (ES = 1.44) and block 2 (*p* = 0.0003) (ES = 1.88) but not in blocks 3 and 4 (*p* = 0.1664, ES = 0.92 and *p* = 0.0899, ES = 0.87, respectively). Also, backs showed lower movement variability in all tackles compared with block 1. In contrast, forwards only showed a clear decrease in the last tackles of the last blocks (Fig. 3D, 3F).

Within block variability when tackling was higher for forwards (CV; 18.7% block 1; 11.63% block 2; 11.06% block 3; 9.11% block 4) vs (14.23% block 1; 7.56% block 2; 10.60% block 3; 12.01% block 4) for backs. Also, box and whisker plots showed more variability within blocks for forwards than backs except in the last block (Fig. 3C, 3E).

No differences were observed in dominant vs. non-dominant shoulder neither in forwards (*p* = 0.067) nor in backs (*p* = 0.345).

Tackled:

The duration of tackled in milliseconds (mean ± SD) was 3775.02 ± 390.33 ms for forwards and 3970.27 ± 376.07 for backs. Figure 4 shows movement variability when being tackled for backs and forwards. Standardised mean differences (Cohen's *d*) and linear mixed-effects model with interactive effects between blocks for dependent variables (SampEn) divided into two positional groups (backs and forwards) for *tackled* are shown in Figure 4A. In backs, significant differences were observed in block 1 vs 4 (*p* = 0.0025) (ES = -1.340), but not in block 1 vs 2 (*p* = 0.0756) (ES = -0.770) or block 1 vs 3 (*p* = 0.2321) (ES = -0.430). No significant differences were observed in any of the studied block comparisons in forwards (block 1 vs 2, *p* = 0.2779, ES = 0.270; block 1 vs 3, *p* = 0.8949, ES = -0.030; block 1 vs 4, *p* = 0.1830, ES = -0.300). Figure 4B shows SampEn (mean ± SD) and T-test analysis for differences between positions within each block. Significant between-position differences were observed in block 1 (*p* = 0.0007) (ES = 1.28) and block 3 (*p* = 0.0118) (ES = 1.56) but not in blocks 2 and 4 (*p* = 0.3939, ES = 0.36 and *p* = 0.2132, ES = 0.47, respectively). Also, backs showed higher movement variability in all tackles compared with block 1, in contrast forwards only showed a clearly decrease in the last tackles of the last block (Fig. 4D, 4F).

Within block variability when being tackled showed higher levels of variability for forwards (CV; 20.16% block 1; 14.63% block 2; 12.97% block 3; 20.72% block 4) than for backs (11.71% block 1; 14.61% block 2; 7.90% block 3; 15.14% block 4). Also, box and whisker plots show a higher within-block variability in forwards than in backs except in block 2 (Fig. 4C, 4E).

No differences were observed in dominant vs. non-dominant shoulder neither in forwards (*p* = 0.482) nor in backs (*p* = 0.695).

DISCUSSION

This study aimed to identify changes in movement variability between positions (forwards vs. backs) in cumulative tackles events training during both attacking and defensive roles in rugby league. To our knowledge, this is the first study to analyse movement variability in tackling actions. The main findings are that movement variability is progressively reduced with cumulative tackle events over blocks (i.e. six *tackling* and six *tackled*), especially for backs and defensive tackles. Overall, forwards present the lower movement variability in all blocks than backs. Previous research suggests that movement variability might be reduced by different factors; on the one hand as a function of practice or experience [51, 62], and on the other hand because of aging [27], disease [27], injury [63] or fatigue [64]. Therefore, since forwards perform more collisions during the course of a match [12] this might suggest that forwards adjust better to tackle actions.

In the current study, it appears that forwards maintain their levels of movement variability without significant changes during cumulative tackle events. In contrast, backs present higher levels of movement variability in block 1 and suffer significant decreases with cumulative tackle events. In such a manner, when the interactions among elements in the system worsen, the movement variability could be reduced affecting locomotor outputs [27]. Gabbett and Ryan (2009) [18] found that the greatest improvements in tackling technique occurred in the players with the lowest initial technical tackling ability. This behaviour has also been found in the present study, since the players who presented higher initial levels of movement variability showed the greatest decreases in movement variability. Thus, the between-position differences observed in movement variability initial values and its behaviour during cumulative tackle events are probably associated with specific positional requirements [12].

Cummins & Orr (2015) [12] showed that both forwards and backs experienced more collision events in defence than attack. Consequently, the principal focus of the tackle task should be set on defensive tackles because these may prove crucial in determining match outcomes [6]. Running speed is progressively reduced when players (especially backs) are required to perform a high number of collisions per minute [20]. The present study shows a similar behaviour in movement variability, especially in tackling actions. The major difference was produced between block 1 and 4 with a small decrease in movement variability in forwards and large changes with significant differences in backs (Fig. 3A). This highlights that the decrease in movement variability in backs is due to the fact that the majority of the tackles are below the average of the entropy values of block 1 (Fig. 3D). However, and in forwards only, the last tackles in blocks 3 and 4 are below the average of block 1 (Fig. 3F). Also, a clear association between the decrease in movement variability and an increase in the number of contact effort in defensive actions exists (Fig. 3B). In this sense, if movement variability is low it might harm a player's tackling ability, and in turn potentially increase the risk of injury [63], so a change in the structure of the task could be suggested. The attacking play of hit ups and the ability to tolerate physical collisions is important for rugby league players [12]. Similar to tackling actions, when participants were being tackled both positional groups showed a progressive reduction in movement variability. However, the last block was only significantly different in backs (Fig. 4A).

Understanding the tackle characteristics and quantifying its load should be an essential part of load monitoring in rugby and could be associated with tackle performance [4]. Current tackle analysis using microtechnology is limited to counting the number of tackle events and their magnitude. Until now, the most widely used tool is an algorithm designed specifically for rugby league, which quantifies collision counts [65]. This algorithm is sensitive to detect 97.6% of collision events during professional rugby league match-play [65]. However, Glazier & Davids (2009) [66] state that it is the structure,

rather than the magnitude, of variability is important in uncovering the functionality of this ubiquitous feature of human motor behaviour. Moreover, Wu *et al.* (2014) [67] suggested that the temporal structure of motor output variability can explain differences in how individuals adapt to different types of dynamics. The differences found between backs and forwards in entropy calculated from accelerometers in our study reflects the different forms of adaptation to the environment derived from the specificity of the training by positions in the same team and probably should be taken into account to plan the training. Thus, entropy could be a good alternative tool to analyse the temporal structure of variability in tackle actions and to understand the differences in locomotor outputs between position when performing multiple collisions training.

Futures studies should focus on analysing changes in movement variability during open tasks with decision-making components and during match play and if it is associated with match-play tackling performance. Furthermore, commercially available accelerometers usually sample at a frequency of 100 Hz [17], so the validity of tri-axial accelerometers sampling at 100 Hz for calculating entropy in short actions like a tackles frequencies should be assessed to fully understand if this analysis can be extended to other commercially available devices.

Limitations

The current study was performed on a single professional rugby league academy squad and during a single standardised training session with controlled tackling and tackled movements. While the number of tackles analysed was 528, more than the match demands reported for professional rugby league [52], the tackle was performed in a controlled setting and may not fully represent real match conditions. Studying the tackle in controlled settings however, allows for experiential and explorative study designs, which offers deeper insight into the demands and patterns of the movement [68]. Also, when considering the findings between positions, it is worth noting that tackle event occurred within the same position i.e. forwards competed against forwards, and back competed against backs. As such, how tackle variability may behave when a forward competes against a back (on attack and defence) is not known, and a potential avenue for future research. Also, the participants were elite adolescent male rugby league players, so the findings of this study can be useful for researchers and practitioners working at the elite level.

CONCLUSIONS

To our knowledge, this is the first study to use entropy analysis to quantify the changes in movement variability in cumulative tackle events in elite rugby players. In conclusion, movement variability is progressively reduced with cumulative tackle events, especially in backs and in the defensive role. Forwards present lower movement variability values in all blocks, particularly in the first block, both in the attacking and defensive role.

Practical Implications

- (1) Entropy measures can be used by practitioners as an alternative tool to analyse the temporal structure of variability of tackle actions and to quantify the load of these actions by positions.
- (2) Movement variability analysis can help to maintain the optimal complexity in repetitive tackle tasks between positions.
- (3) Practitioners should modify the contact tasks between positions to adjust the complexity of the task to the different requirements of each position and difference collisions-profiles to optimize the training process.

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Conflict of interest declaration

The authors declare no conflict of interest.

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Karatekas educated on injury prevention and supported by fitness coaches are more likely to practise injury prevention

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ABSTRACT: To determine the current perceptions and practices of top-level karate athletes concerning risk factors and injury prevention programme (IPP) implementation in training and competition. Out of 90 eligible countries (933 athletes) participating in the karate World Senior Championships (WSC) in Madrid 2018, 50 countries (55.6%) represented by 137 athletes (14.7%; 52 females and 85 males) responded to a structured questionnaire. Of the athletes responding, 45% reported that their national team did not conduct any measures to reduce injury risk (43% among females and 47% among males; $p = 0.68$). Kumite athletes (51%) were more likely to practise injury prevention compared to kata athletes (25%; $p = 0.016$). Of the respondents, 69%, 60%, 60% and 34% reported having no team doctor, fitness coach, massage therapist and physiotherapist, respectively. A greater proportion of athletes who had access to a fitness coach (part-time or full-time) engaged in injury prevention strategies (67% and 51%, respectively) than those who did not (35%; $p = 0.031$). Athletes who had received previous advice about injury prevention were more likely to practise injury prevention (58%) compared to the rest (21%; $p < 0.001$). The current study revealed that: i) almost half of the karatekas already benefited from an injury prevention programme, ii) injury prevention programmes were practised more frequently when there was a fitness coach among their coaching staff, iii) karatekas who had received education about injury prevention were more likely to practise injury prevention programmes.

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INTRODUCTION

In competition, prospective studies have shown that karate athletes sustain on average one injury every 25 min of combat, although the large majority of these are minor or mild in severity [1]. This remarkable injury rate, equivalent to 2400 injuries per 1000 competition hours, exists despite efforts by the World Karate Federation (WKF) to mitigate risk of injury by regularly revising the rules of the game to protect the health of the karateka [2]. In training, very few studies, using survey data, have shown that training related injuries represent 76 to 90% of all injuries [3, 4]. Indeed, competitions are just the end process of a karate athlete's preparation and do not account for exposure during training and sparring combat. Studying only competition injuries therefore does not provide a complete measure of injury risk, and could lead to selection and survivorship bias [5], because non-selected and/or injured athletes who could not participate in competitions are simply ignored. Therefore, it is important to implement effective strategies to prevent injuries in both training and competition.

However, studies related to injury prevention programmes (IPPs) in karate are lacking. Recently, IPPs have gained considerable attention in many sports [6–8], as injury prevention is considered important to minimise the associated treatment costs, participation loss and long-term negative side effects for the athletes [9]. In addition, scientific evidence, especially in football, has demonstrated that these programmes can significantly prevent injuries [10–13]. Before studying the efficacy of any IPP, it is important to understand the reality of IPP implementation and end-users' perceptions toward IPP [8], including why karate athletes do, or do not, adopt IPPs. This would generate a better understating of the factors influencing successful implementation of IPPs.

Therefore, the purpose of the present study was to determine the current perceptions and practices of top-level karate athletes concerning risk factors and injury prevention programme (IPP) implementation in training and competition.

MATERIALS AND METHODS

Design

Cross-sectional study based on face-to-face surveys.

Participants

A total of 1117 athletes (140 countries) participated in the karate World Senior Championships (WSC) in Madrid, 2018. Because of the language barrier, 933 athletes (90 countries) were potentially eligible to answer the available questionnaire languages (English, French, Slovak, and/or Spanish). During the pre-event official medical meeting, the Chairman of the World Karate Federation Medical Commission presented the project and invited the team doctors to inform their athletes about the face-to-face survey and ask them to present at least one athlete as a representative of the team to conduct the questionnaire. Data were collected between 6th and 11th November 2018 and athletes were asked to base their responses on their programmes and experiences from the past season (2017–2018). All participating athletes signed informed written consent to participate.

This study was approved by the Ethics Committee of the Faculty of Physical Education and Sports, Comenius University, Bratislava, Slovakia (reference number 13/2019).

Survey

The survey was constructed in English, French, Slovak, and Spanish. The questionnaire consisted of 15 questions (see online supplementary appendix *Injury Prevention WKF questionnaire*) with four sections: (i) injury prevention implementation overview, (ii) perceptions and attitudes towards injury prevention, (iii) perceived injury risk and

injury prevention practice by body part, and (iv) perceived injury risk factors.

The design of the survey took into consideration the authors' combined knowledge and experience of sports medicine and sports science in elite karate. The survey was pilot tested with 20 high-level karate athletes (who did not participate in the WSC) before the start of the study. The received feedback and comments were taken into consideration and changes were made in response to these.

Survey analysis

Raw data were entered separately by DC and LP from paper questionnaires to Microsoft Excel and then double-checked case by case by MT. The data were analysed using the SPSS 22.0 program for Mac OS X (SPSS, Inc., Chicago, IL, USA). Crosstabs using chi-square tests were used to analyse proportions.

RESULTS

Survey information

Out of 90 countries (933 athletes) eligible to the survey languages, 50 countries (55.6%) represented by 137 athletes (14.7%; 52 females and 85 males) completed the questionnaire. However, 416 athletes did not volunteer and 380 could not be reached.

IPP overview and athletes' perception and attitude toward injury prevention

Of the athletes responding, 45% reported that their team had not conducted any preventive measures to reduce injury risks (43% among females and 47% among males ($p = 0.68$). Kumite athletes (51%)

TABLE 1. Medical and technical staff availability in top-level karate athletes according to injury prevention implementation status

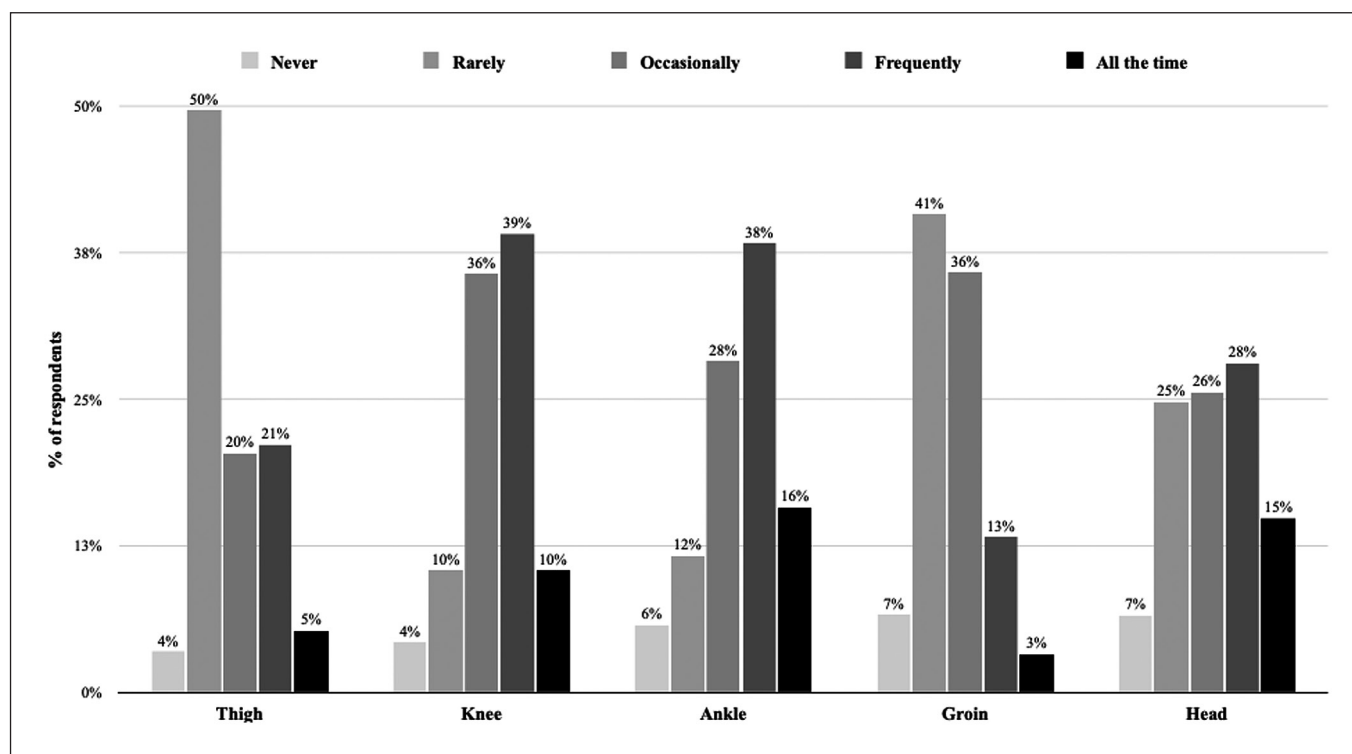
	Number of athletes who Practiced injury prevention with their team (%)	Number of athletes who never Practiced injury prevention (%)	p-value
Team Doctor			
No	30 (43.5)	39 (56.5)	0.833
Yes, Part time	8 (44.4)	10 (55.6)	
Yes, Full time	15 (50)	15 (50)	
Physiotherapist			
No	12 (35.3)	22 (64.7)	0.283
Yes, Part time	22 (45.8)	26 (54.2)	
Yes, Full time	20 (54.1)	17 (45.9)	
Massage therapist			
No	24 (40)	36 (60)	0.318
Yes, Part time	13 (48.1)	14 (51.9)	
Yes, Full time	17 (56.7)	13 (43.3)	
Fitness coach			
No	21 (35)	39 (65)	0.031*
Yes, Part time	14 (66.7)	7 (33.3)	
Yes, Full time	18 (51.4)	17 (48.6)	

* significant difference ($P < 0.05$).

TABLE 2. Perception and attitude of top-level karate athletes toward injury prevention

	Number of athletes Practiced injury prevention with their team (%)	Number of athletes never Practiced injury prevention (%)	<i>p</i> -value
Have you previously received advice about injury prevention programs			
Yes	40 (58)	29 (42)	P < 0.001*
No	9 (20.5)	38 (79.5)	
Importance of injury prevention			
Low or Moderate	7 (47)	8 (53)	0.841
High	47 (44)	60 (56)	
It is more important to use the training time to play karate than to conduct injury prevention			
Fully agree or Agree	34 (50)	34 (50)	0.356
Disagree or Fully disagree	12 (36)	21 (64)	
Not sure	8 (38)	13 (62)	
Attitude towards injury prevention measures			
Positive or Very Positive	49 (45)	60 (55)	0.548
Neutral or Negative or very negative	4 (33)	8 (67)	

* significant difference (P < 0.05).


FIG. 1. Injury risk perception related to injury body part.

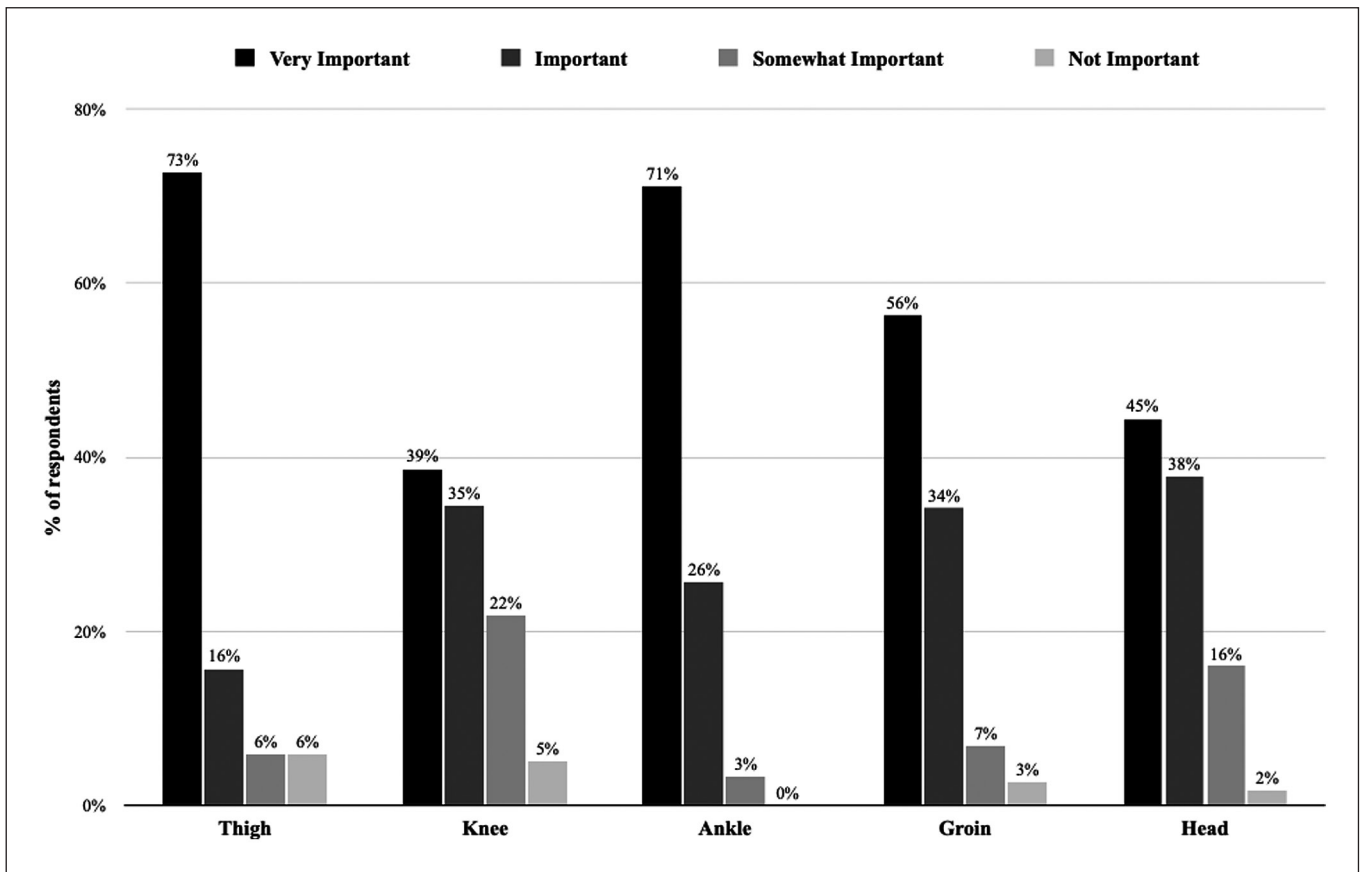


FIG. 2. The perceived injury prevention importance by body part.

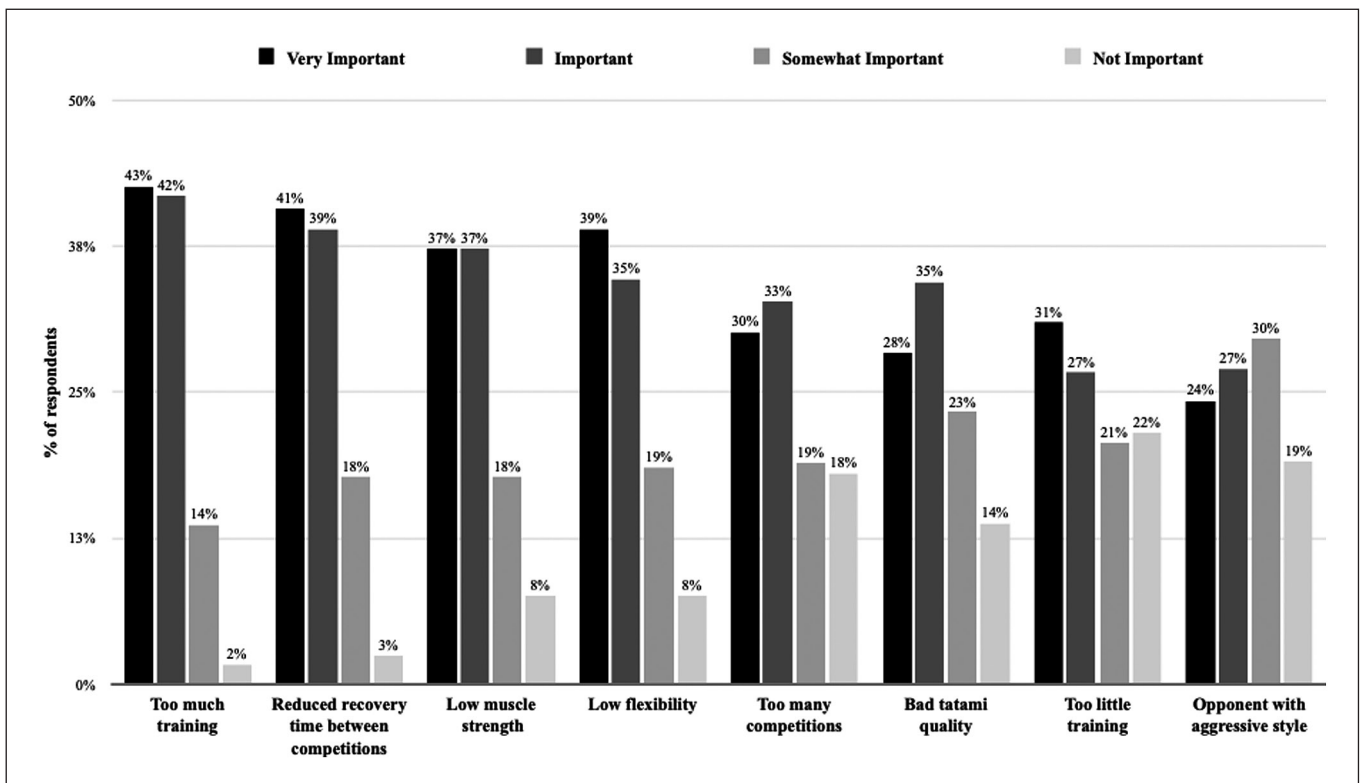


FIG. 3. Perception of risk factors by importance

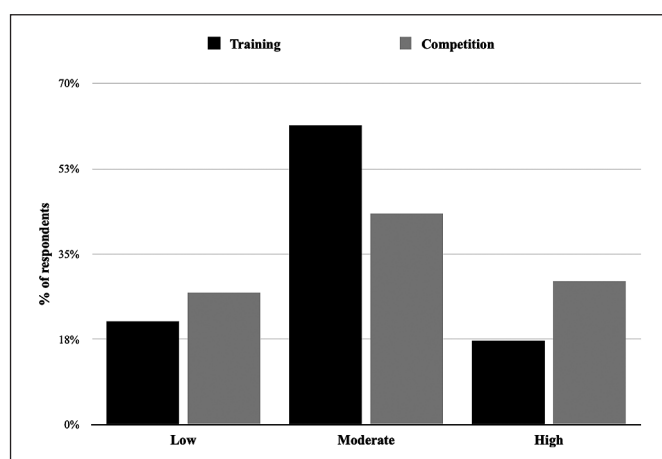


FIG. 4. Training vs. competition injury risk perception.

were more likely to practise injury prevention compared to kata athletes (25%; $p = 0.016$). Among the respondents, 69%, 60%, 60% and 34% had no team doctor, fitness coach, massage therapist and physiotherapist, respectively. Athletes who had a fitness coach (part-time or full-time) employed better injury prevention strategies (67% and 51%, respectively) compared to athletes who did not have a fitness coach (35%; $p = 0.031$).

The availability of medical and technical staff in the teams and the relationship with injury prevention practice are presented in Table 1.

Athletes who had received previous advice about injury prevention were more likely to practise injury prevention (58%) compared to those who had not received any advice (21%; $P < 0.001$). As many as 88% of the participating athletes thought that injury prevention is important in karate, while 90% of respondents had a positive or very positive attitude towards injury prevention measures.

The perception and attitude of the karate athletes toward injury prevention are presented in Table 2.

Perceived injury risk and 'importance' of injury prevention according to body parts

Of the surveyed athletes, 54%, 50% and 43% responded that the ankle, knee, and head were the most frequently (frequently or all the time) injured body parts. Their perceived importance of injury risk according to body part is detailed in Figure 1.

The most important body parts that karate athletes think should be protected most are the thigh, knee and ankle. Participants' perceived 'importance' of injury prevention regarding body parts is presented in Figure 2.

Perceived injury risk factors

The perception about injury risk in competition compared to training is presented in Figure 3. Based on perceived rating of importance by

athletes, the three most important risk factors for injury are presented in Figure 4.

DISCUSSION

This is the first study to directly observe the beliefs and considerations of IPP and provides insights into the perceptions of IPP in elite karate. The current results reveal that: i) 45% of the participating athletes reported that their team had not conducted any preventive measures to reduce injury risks, ii) injury prevention programmes were practised more frequently when the athletes had a fitness coach, iii) athletes who had received previous advice about injury prevention were more likely to practise injury prevention programmes, and iv) the main risk factors for injuries were thought to be 'too much training', 'lack of recovery time between competitions', and 'low muscle strength'. The findings of this study will help inform practitioners about the barriers and facilitators of IPP in elite karate.

IPP overview and athletes' perception and attitude toward injury prevention

In the present study, nearly half of the participating athletes reported that they had not conducted any preventive measures to reduce injury risks. Much of the research on IPP so far has focused on team sports, with player adherence identified as a key factor for IPP success [12]. However, the results of this study indicated that this low implementation rate could not be linked to players' adherence, as almost all of the respondents reported that an injury prevention programme is important to reduce injury occurrence and were positive or very positive towards injury prevention measures.

Whilst athletes are the intended health beneficiaries of IPP, team staff also play a key role in achieving the desired injury prevention [14]. In the present study, most respondents were not supported by medical staff – there was no team doctor, fitness coach, massage therapist or physiotherapist. Consequently, the low implementation rate could be linked to the availability of the individuals delivering programmes within the team. Indeed, there was a greater proportion of athletes who had a fitness coach (part-time or full-time) than those without one. Two-thirds of respondents reported having a physiotherapist available in their team. Our findings reinforce previous studies from professional football, emphasizing the key role of fitness coaches and physiotherapists in the implementation of IPP. O'Brien et al. [15] found that in football, fitness coaches were responsible for delivering the IPPs, while physiotherapists assisted with the supervision and correction of exercises.

The current study also shows that player education is a key factor and major point of divergence when it comes to practising compared to never practising injury prevention. Indeed, respondents who had received previous advice about injury prevention were nearly three times more likely to practise IPP compared to karatekas who had not received any advice. This aligns closely with the fact that education and communication of scientific evidence play an important role in convincing players about injury prevention benefits [8, 12]. The

findings suggest that team managers should ensure the availability of at least part-time fitness coaches and physiotherapists within their teams.

Perceived 'importance' of injury prevention according to body parts

A recent systematic review and meta-analysis on injury epidemiology in WKF karate indicated that the most commonly injured body parts were the head and neck, and the lower limbs [11]. Despite the fact that the 28 studies included in this meta-analysis were all from competitions (e.g. championships and tournaments), a similar distribution was reported by our respondents, with ankle, knee and head/face injuries perceived as the most frequent (without differentiating between training and competition). Interestingly, in the current study, athletes did not clearly distinguish between body parts when asked about their prevention priorities. It seems that karatekas have a relatively accurate picture of the injury epidemiology, yet do not make any clear differentiation when it comes to preventing injuries. For them, all body parts seem nearly equally important. This is an interesting observation and may simply reflect that injury to any small body part (e.g. a broken finger) could stop the athlete from practising karate. Therefore, this is a point of reflection for clinicians. Should we focus on the most frequent/serious injuries for prevention, and ignore the rare ones, or should we consider any injury as a potential threat to the athletes' career and therefore consider prevention more broadly?

Perceived injury risk factors

The main perceived injury risk factors in the current study were: 'too high training load', 'too short recovery period between competitions', 'lack of muscle strength' and 'lack of flexibility'. This is consistent with Destombe *et al.* [3], who previously suggested that 'more time spent training each week' was associated with an increased risk of injury in karate. On the other hand, recent studies in football have indicated that lack of recovery between matches and high training load were perceived by the practitioners as the two main key extrinsic risk factors for injury [12, 13]. Therefore, the monitoring of training load could appear as crucial in preventing injuries among elite karatekas. In karate, several methods using competition/training duration and heart rate or rating of perceived exertion to quantify the training load have previously been validated and could be a useful support for karate practitioners [16–18]. Nevertheless, this issue needs further investigations to verify whether the perception of the athletes turns out to be correct, i.e. that a high training load is actually associated with an increased risk of injuries.

'Lack of muscle strength and flexibility' was considered, in the current study, as a major perceived injury risk factor in karate. This aligns with the few studies focusing on IPP showing that muscle strength and flexibility were frequently assessed from screening tests in elite soccer to prevent non-contact injuries [12, 13, 19]. However, to date, no studies have documented an effect of flexibility training as prevention, and this finding in the present study refers to

karate athletes' view. Indeed, this could be the nature of karate – with greater demands on flexibility than running sports or soccer. It would therefore be interesting to test the effects of an injury prevention programme including both eccentric resistance and flexibility exercises in elite karate.

Arriaza *et al.* [2] reported that the global injury incidence during World Karate Championships was almost double with the old rules compared to the one with the new rules. This was a consequence of a WKF long-term strategy to mitigate the risk of injury during competition. We speculate that the WKF initiative aiming mainly at competitions derived from the fact that scores concerning injuries came mostly from studies that focused on competition, whereas few studies deal with injuries sustained during training [20]. However, the results of the present study confirmed that karate athletes believe they are at the same risk of sustaining injuries in both training and competition. This aligns with previous studies showing the great risk during karate training and reporting that training-related injuries represented between 76% and 90% of total annual injuries in karate [3, 4]. The challenges and opportunities arising from this study need careful consideration by the WKF to reinforce their current strategies of reducing injuries by focusing on IPP during training to prepare for competitions.

Limitations and considerations

There are some limitations to our survey. First, there is a gap concerning the level of some teams/countries, in which resources (e.g., equipment and staff numbers) will vary and will influence the knowledge, attitude and practices of teams. Second, only 137 karatekas participated in this survey (14.7% of all the athletes taking part in the competition). However, the sample represented 50 countries (55.6%), which could provide a general picture of the injury prevention situation in the presented countries. This response rate could be explained by various reasons: (1) gaining access to elite karatekas for face-to-face interview during karate WSC is challenging, (2) the language barrier, as only athletes who spoke English, French, Slovak, Polish, Czech and/or Spanish took part in this study, (3) some athletes deemed the nature of the information to be too sensitive to disclose.

This study provides knowledge about how karatekas perceive the injury prevention programmes. However, this knowledge and good intentions to use it do not guarantee adoption.[21] Key considerations are how these programmes will be delivered and by whom. As noted by O'Brien and Finch (7) and O'Brien and Donaldson (21), it will be essential to address all levels of the system when developing karate injury prevention programmes and their related implementation plans to identify potential barriers (e.g., lack of knowledge, time or programme acceptance) and facilitators to programme adoption.

CONCLUSIONS

The current study revealed that: i) almost half of the karatekas have already benefited from an injury prevention programme, ii) injury prevention programmes are more frequently practised when a fitness

coach is present in the athlete's coaching staff, iii) karatekas who had received education about injury prevention were more likely to practise injury prevention programmes.

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Contributors

MT, DA and RA designed the study and approved the final manuscript. MT conducted the analysis, interpreted the findings and wrote the first draft of the manuscript. JC, DA, KK, KC, and RA reviewed and edited the manuscript. All authors approved the final manuscript.

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Competing interests

MT and JC declare that they have no potential conflicts of interest that are directly relevant to the content of this study. DA is the Chair of the Para-Karate Commission of the World Karate Federation and a member of the Technical Commission of the European Karate Federation and RA is the Chair of the Medical Commission of the World Karate Federation; however, neither DA nor RA received any remuneration from the European Karate Union or the World Karate Federation to conduct this study, and neither the European Karate Union nor the World Karate Federation has had any influence on this work.

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Effects of climbing- and resistance-training on climbing-specific performance: a systematic review and meta-analysis

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ABSTRACT: The objective of this systematic review and meta-analysis was to examine the effects of climbing and climbing-and-resistance-training on climbing performance, and strength and endurance tests. We systematically searched three databases (SPORTDiscus, SCOPUS, and PubMed) for records published until January 2021. The search was limited to randomized-controlled trials using active climbers and measuring climbing performance or performance in climbing-specific tests. Data from the meta-analysis are presented as standardized difference in mean (SDM) with 95% confidence intervals (95% CI). Eleven studies are included in the systematic review and five studies compared training to a control group and could be meta-analyzed. The overall meta-analysis displayed an improvement in climbing-related test performance following climbing-specific resistance training compared to only climbing (SDM = 0.57, 95%CI = 0.24–0.91). Further analyses revealed that finger strength (SDM = 0.41, 95%CI 0.03–0.80), rate of force development (SDM = 0.91, 95%CI = 0.21–1.61), and forearm endurance (SDM = 1.23, 95%CI = 0.69–1.77) were improved by resistance-training of the finger flexors compared to climbing training. The systematic review showed that climbing performance may be improved by specific resistance-training or interval-style bouldering. However, resistance-training of the finger flexors showed no improvements in strength or endurance in climbing-specific tests. The available evidence suggests that resistance-training may be more effective than just climbing-training for improving performance outcomes. Importantly, interventional studies including climbers is limited and more research is needed to confirm these findings.

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INTRODUCTION

Rock climbing has gained increased attention in the past decade and was included in the Olympic games for the first time in 2021. In addition, a growing body of scientific literature is focusing on the physiological demands of the sport, as well as on the relationship between climbing performance and muscular strength and endurance [1]. Competitive climbing consists of three disciplines (speed climbing, lead climbing and bouldering) which differ in their respective physiological demands [2–5]. Of the three, lead climbing and bouldering are the two most practiced and researched disciplines [1]. While bouldering is performed on lower walls (< 6 meters) and often consists of few, but highly explosive and difficult moves [6], lead climbing is performed on high walls (10–30 meters) and usually consists of 20 to 50 moves with repeated, sub-maximal force generation (often referred to as endurance). Climbing performance is quantified using several different difficulty scales, depending on geographical location and discipline. Recently, however, most researchers have adopted the 1–32 numerical scale proposed by the International Rock Climbing Research Association (IRCRA) [7], making comparisons across studies possible.

Whereas climbing performance is challenging to measure reliably, assessment of the factors that may predict climbing performance is more generally applied. In general, performance in the sport of climbing relies on a complex interaction of physiological factors such as flexibility [8, 9], strength [5, 10–15], and endurance [16, 17]. Moreover, the physiological demands of climbing are influenced by factors such as the steepness of the route, the style of climbing, distance between holds, hold size, and the overall difficulty of the climb [18, 19]. While flexibility is challenging to measure [20] and has not yet received much scientific attention, strength in the finger, arm, shoulder and back muscles is relatively easy to measure in a standardized manner and has been identified as an important determinant of performance in this sport [5, 10–15]. In addition, muscular endurance assessed by using sub-maximal, intermittent contractions of the finger flexors has been shown to be related to climbing ability [16, 17].

The physiological demands of rock climbing, and the characteristics of climbers performing on different levels, have been described in previous systematic [1] and narrative reviews [21–23]. To the best

of our knowledge, however, no systematic literature reviews or meta-analyses on the effect of training on climbing performance and climbing-related factors have been performed. As the training and measurement techniques vary between studies, a systematic appraisal of the current knowledge could assist researchers and athletes in the selection of prospective training and research designs. Thus, the objective of the current systematic review and meta-analysis was to assess and compare the effects of climbing- and resistance-training on climbing performance and performance in sport-specific strength-and-endurance-tests.

MATERIALS AND METHODS

Literature search

The study complies with the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) [24]. We systematically searched for published randomized control trials (RCTs) examining the longitudinal effects of climbing- and resistance-training on climbing performance or performance in sport-specific tests on October 20th, 2020. Peer-reviewed articles published in English were identified from three electronic databases: SPORTDiscus, SCOPUS, and PubMed. The following search terms were used: (“rock climb*” OR

“sport climb*” OR “lead climb*” OR “climbers” OR “boulder*”) AND (“finger strength” OR “finger endurance” OR “forearm strength” OR “forearm endurance” OR “grip strength” OR “crimp” OR “finger flexor*” OR “training” OR “fingerboard” OR “hangboard”). The search identified 743 records (SPORTDiscus: 231; SCOPUS: 293; PubMed: 219). The search was repeated in the same databases on December 13th, 2021, to identify articles published after the original search. Any previously identified records were removed as duplicates. This search identified three new records published in 2021 [25–27]. All identified records were imported to EndNoteX9 and merged into one valid library to allow for removal of duplicate records [28]. After elimination of duplicates, 279 records remained (Figure 1).

Inclusion criteria and selection process

Three authors (NS, VA and AHS) independently assessed the titles and abstracts of the studies for eligibility. In case of disagreement, subsequent consensus by discussion was reached. We included only RCTs involving active climbers of any discipline and performance level examining the effect of climbing- or resistance-training on climbing performance or climbing related physical performance such as static and dynamic finger and core strength.

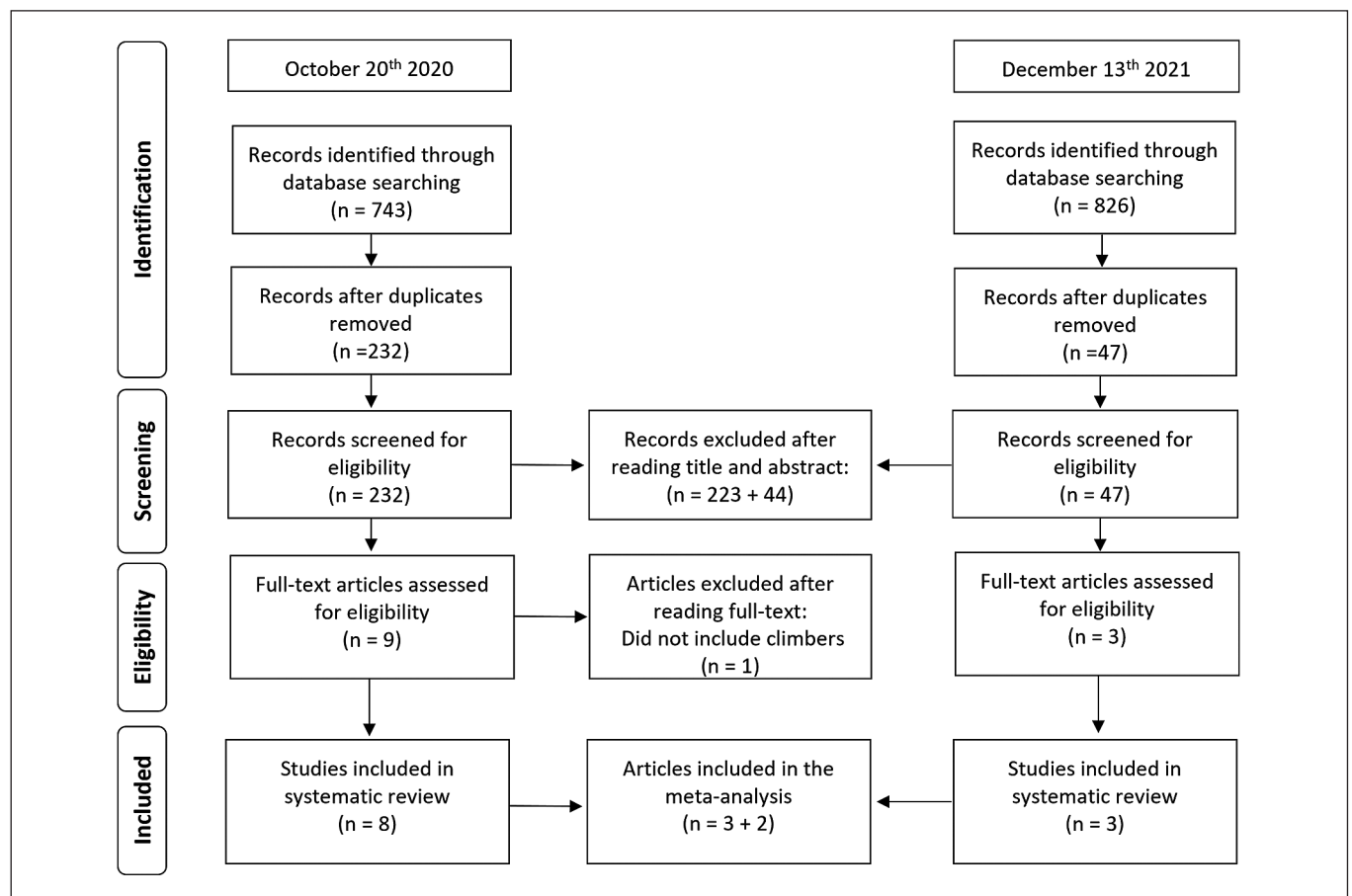


FIG. 1. Flow chart showing the study selection procedure.

Methodological quality

The 11-item Physiotherapy Evidence Database (PEDro) scale was used to rate the methodological quality and risk of bias of the included studies [29]. This scale has previously displayed a high validity [30]. Four authors (NS, VA AHS, and AR) assessed the methodological quality independently with subsequent consensus by discussion. Please see Table 1 for an overview of the items and each of the studies' individual score. Of the 11 items, the first item of the PEDro scale concerns external validity and is not included in the total score, leaving a maximal available score of 10 [31]. Studies with a total PEDro score > 6 were considered high-quality studies with low risk of bias [32].

Data extraction and analysis

Data extraction was completed in accordance with the Cochrane handbook for systematic reviews of interventions [28]. NS and AR

conducted data extraction of study results separately and settled discrepancy by mutual agreement. Studies were found appropriate for meta-analysis [25, 27, 33–35] if they performed any climbing- or resistance-training method in the intervention group and compared the changes to a passive (i.e., no climbing or climbing-specific training) or active (i.e., climbing- or resistance-training as usual) control group. Changes in finger strength were extracted from Levernier and Laffaye [33], and Medernach et al., [34], and Stien et al. [27] while changes in dead hang duration were extracted from Medernach et al. [34] and Hermans et al. [35]. When several outcomes were presented in the same intervention, only one outcome was included in each meta-analysis. Finger strength was prioritized over rate of force development (RFD) and dead-hang duration in the main analysis. Finger strength was prioritized because 1) this was the most reported outcome in the included studies and 2) has been identified as a crucial determinant of climbing performance [11, 14]. Other

TABLE 1. The methodological quality of the included studies, as assessed using the PEDro scale [29], the sample size (*n*) needed to obtain $\alpha = 0.05$ & $\beta = 0.2$, and post hoc calculated power with $\alpha = 0.05$ for the studies included in the meta-analyses [41].

Study	Eligibility specified	Randomization	Allocation concealed	Similar at baseline	Blinding of subjects	Blinding of therapists	Blinding of assessors	< 15% drop-out	Intention to treat	Between groups statistics	Point and variability measures	Total score	n for $\alpha = 0.05$ and $\beta = 0.2$	Statistical power with $\alpha = 0.05$
Hermans, et al. [35]	1	1	1	1	0	0	0	0	0	1	1	5	502	83.9
Levernier and Laffaye [33]	1	1	1	1	0	0	0	0	0	1	1	5	6	99.9
López-Rivera and González-Badillo [39]	1	1	1	1	0	0	0	0	0	1	1	5		
López-Rivera and González-Badillo [38]	1	1	1	1	0	0	0	0	0	1	1	5		
Saeterbakken, et al. [36]	1	1	1	1	0	0	0	1	0	1	0	5		
Philippe, et al. [40]	1	1	1	1	0	0	0	1	0	1	1	6		
Stien, et al. [27]	1	1	1	1	0	0	0	1	0	1	1	6	78	31.0
Mundry, et al. [25]	1	1	1	1	0	0	0	1	0	1	1	6	456	6.1
Medernach, et al. [34]	1	1	1	1	0	0	0	1	1	1	1	7	126	18.5
Medernach, et al. [37]	1	1	1	1	0	0	0	1	1	1	1	7		
Stien, et al.[26]	1	1	1	1	0	0	0	1	1	1	1	7		

1 = criterion is satisfied/fulfilled, 0 = criterion is not satisfied/fulfilled

parameters (e.g., bent-arm hang and climbing performance) that were only examined in one study, or were not measured or trained in comparable ways, were excluded from the meta-analysis. Studies that fulfilled the inclusion criteria but did not use a control group [26, 36–40] were excluded from the meta-analysis and included in the systematic review.

Statistical analyses

Extracted data from individual studies were collated in Excel (Microsoft) and meta-analyses were performed in Comprehensive Meta-Analysis (CMA) V.3 (Biostat, Englewood, New Jersey, USA). The meta-analyses were performed with random effects models, and effect estimates are presented as standardized difference in mean (SDM) with 95% CI. Heterogeneity is presented as I^2 and p-values. Potential publication bias was assessed by funnel plot and Begg and Mazumdar rank correlation test. Post hoc power calculations with $\alpha = 0.05$ and adequacy of sample size in each of the included studies was assessed by calculation of the sample size required for the effect in each study to obtain an alpha of 0.05 and a beta of 0.2 using an online calculator [41]. As normality is an important assumption for meta-analyses, skewness of the outcomes was assessed as baseline mean/SD and variables with a mean to ratio > 2 were considered skewed [42]. The significance level was set to $p < 0.05$.

RESULTS

Study characteristics

Finally, the same three authors read the full-texts of the remaining twelve studies and agreed to remove one due to not fulfilling the inclusion criteria of including active climbers. The reference lists of the included papers were manually searched to discover additional relevant studies. However, this method yielded no further results. The present systematic review consists of eleven published studies comprising 225 climbers (Table 2). The overall meta-analysis comprised 110 climbers from 5 studies [25, 27, 33–35]. The trials compared the effect of resistance-training with climbing on performance in climbing-specific strength- and endurance-tests. Stratified analyses were performed on two studies [34, 35] investigating the effect of resistance-training on dead hang ability comprising 53 climbers, and four studies [25, 27, 33, 34] investigating the effect of finger resistance-training on finger strength comprising 80 climbers. The six studies [26, 36, 37, 39, 40, 43] not included in the meta-analyses, due to not including a control condition, comprised 115 climbers.

A heterogeneity was observed for the study samples of the studies included in this systematic review and meta-analysis. Specifically, the performance levels ranged from lower-grade climbers [35] to elite and top internationally-ranked athletes [33]. This challenges

TABLE 2. Characteristics of the included studies.

	Subjects (n, sex, age)	Performance level	Intervention	Control	Outcomes
López-Rivera and González-Badillo [39]	8 m, 1 f 30.4 ± 3.9	Advanced and elite sport climbers IRCRA ≥ 23	Fingerboard training 4 wk MED + 4 wk MAW 4 wk MAW + 4 wk MED		Finger strength: 5 s hang 15 mm edge max load, Finger endurance: half crimp dead hang 11 mm edge
Medernach, et al. [34]	23 m, 25.6 ± 4.4	Highly advanced male boulderers IRCRA = 23	Fingerboard training: 4 wk, 3 × 150 min per wk	Bouldering: 4 wk, 3 × 150 min per wk	Handheld Dynamometry, Dead hangs (19 mm), Intermittent finger hangs (30 mm)
Medernach, et al. [37]	24 m, 25.2 ± 4.8	Advanced boulderers IRCRA = 22	Interval bouldering, 4 wk, 3 × 150 min per wk	Conventional bouldering, 4 wk, 3 × 150 min per wk	Intermittent hangs (30 mm), Climbing-time to exhaustion
Hermans, et al. [35]	30 m/f 23.3 ± 1.9	Lower-grade and intermediate climbers IRCRA = 8–13	Upper-body resistance training: 10 wk, 7 exercises × 4 sets × 5RM, 2 times per wk 10 wk, 7 exercises × 2 sets × 20RM, 2 times per wk	Continued climbing/training as usual	Climbing performance, Dead-hang, Bent-arm hang, 12RM pull-down on machine

TABLE 2. Continue.

	Subjects (n, sex, age)	Performance level	Intervention	Control	Outcomes
Saeterbakken, et al. [36]	13 m, 6 f 27.4 ± 6.7	Elite and Advanced climbers IRCRA = 20.1 ± 3.1	Trunk muscle training: 10 wk 4 Isometric exercises, 3–4 sets × 4–10 reps, × 2 /wk 10 wk 4 dynamic exercises, 3–4 sets × 4–10 reps, × 2 /wk		Body lock-off, Body-lift, Superman, Isometric core strength tests, Finger hang test
Levernier and Laffaye [33]	14 m, 26.1 ± 2.2	Elite and top world-ranking climbers IRCRA ≥ 25	Isometric half-crimp strength: 4 wk, 6 exercises, 2 series of 4–6 s effort, 3 times pr wk	Continued climbing/training as usual	Max isolated finger strength and RFD
López-Rivera and González- Badillo [38]	23 m, 3 f, 32.0 ± 6.2	Advanced and elite sport climbers Mean IRCRA = 22	Fingerboard training 8 wk max weight hangs 8 wk intermittent hangs		Finger endurance: half crimp dead hang 11 mm edge
Philippe, et al. [40]	15 m, 8 f, 25.5 ± 6.7	Elite climbers IRCRA = 20.8 ± 2.0	8 wk climbing-specific muscle endurance training 8 wk climbing-specific hypertrophy training		On sight climbing 17 m Overhang: 27.9° 48 moves
Stien, et al. [27]	16 m, 30.3 ± 7.4	Advanced and elite climbers IRCRA = 21.2 ± 2.7	5 wk campus board training Volume divided over 2 weekly sessions Volume divided over 4 weekly sessions	Continued climbing/training as usual	Bouldering, campus board performance, isometric pull-up strength and RFD (jug and 23 mm rung), arm circumference
Stien, et al. [26]	11 m, 3 f, 27.3 ± 5.3	Intermediate and advanced climbers, IRCRA = 16.3 ± 2.4	Climbing training 5 wk, three weekly sessions (2 lead and 1 boulder) 5 wk, three weekly sessions (1 lead and 2 boulder)		Lead climbing, bouldering, forearm endurance (intermittent test), Max isolated finger strength (23 mm rung), isometric pull-up strength and RFD (jug and 23 mm rung)
Mundry, et al. [25]	15 m, 12 f, 24.7 ± 3.5	Intermediate to advanced IRCRA = 14 ± 4	Fingerboard training 8 wk MED 8 wk MAW	Continued climbing/training as usual	Grip strength in 7 different pinch grip positions and handgrip dynamometry

m = males, f = females, n = number, IRCRA = International Rock Climbing Research Association grade reported in the studies, wk = week, s = seconds, mm = millimeters, RFD = rate of force development, MED = minimum edge depth, MAW = maximal added weight.

the ability of this systematic review and meta-analysis to provide recommendations for specific performance levels. However, the variability in performance levels within studies was generally low. Unfortunately, some studies [35, 36, 40] failed to specify the predominant discipline of the participants. Current recommendations [7] suggest that studies should report how climbers classify their participation in the sport (e.g., sport climber, boulderer, speed climber, etc.) to allow for more detailed interpretation of the findings. It is further recommended that studies report the percentage of time devoted to each discipline [7], which none of the studies included in the present review did.

Quality of the studies

Five studies [33, 35, 36, 38, 39] fulfilled five items on the PEDro scale and the remaining studies fulfilled 6 [25, 27, 40] or 7 items [26, 34, 37]. All studies had eligibility specified, concealed allocation, randomized the climbers into groups and the groups were similar at baseline (Table 1). None of the studies blinded the allocation of the climbers to the investigators and assessors, or the climbers themselves. Moreover, none of the studies with dropouts conducted intention-to-treat analyses.

Results from the meta-analysis

In an overall analysis combining nine trials from five studies comparing the effect of resistance-training and a control condition [25, 27, 33–35], resistance-training improved performance in climbing-specific tests (dead-hang duration or finger strength) compared to regular climbing-training (SDM = 0.57, 95%CI = 0.24–0.91; Figure 2). The included studies were not heterogeneous ($I^2 = 0\%$, $p = 0.47$). The SDM for the studies included in the stratified analysis were not heterogeneous ($I^2 = 0\%$, $p > 0.72$). The funnel plot and the Begg and Mazumdar Rank Correlation Test ($p = 0.174$) did not indicate publication bias (please see Supplementary Figure 1)

and the classic fail-safe N was 20, indicating that there must be 20 unpublished studies to bring the effect of finger resistance training on finger strength to a $p > 0.05$. One of the five studies included in the meta-analysis included an adequate number of participants to obtain an $\alpha = 0.05$ and a $\beta = 0.2$ and two of the studies had a statistical power $> 80\%$ (Table 1). None of the baseline performance data were skewed.

Meta-analysis of finger strength

The meta-analysis of the effects of finger resistance-training included seven trials from four studies [25, 27, 33, 34]. All studies compared fingerboard training with a control group that continued climbing training as usual, and tested finger strength using a half-crimp grip on a climbing-specific hold, either in isolation or with an unconstrained elbow. The analyses revealed that finger strength was improved by specific, isometric finger resistance-training compared to climbing training (SDM = 0.41, 95%CI = 0.03–0.80) (Figure 3).

Meta-analysis of rate of force development

The effect of finger training on rate RFD was assessed in two studies including three trials [27, 33]. The studies compared finger- or campus-board training with a control group that continued climbing training as usual, and tested RFD using a hand dynamometer (half crimp) and isometric pullup on a 23 mm rung. RFD was improved by finger strength training compared to climbing as usual (SDM = 0.91, 95%CI = 0.21–1.61; Figure 4). The SDM for the studies included in the stratified analysis were not heterogeneous ($I^2 = 0\%$, $p > 0.87$).

Meta-analysis of dead-hang endurance

For dead-hang endurance, a stratified analysis of three trials from two studies [34, 35] was performed. The training included isolated, isometric resistance-training on a climbing-specific hold [34], or forearm curls using dumbbells [35]. Dead-hang duration assessed

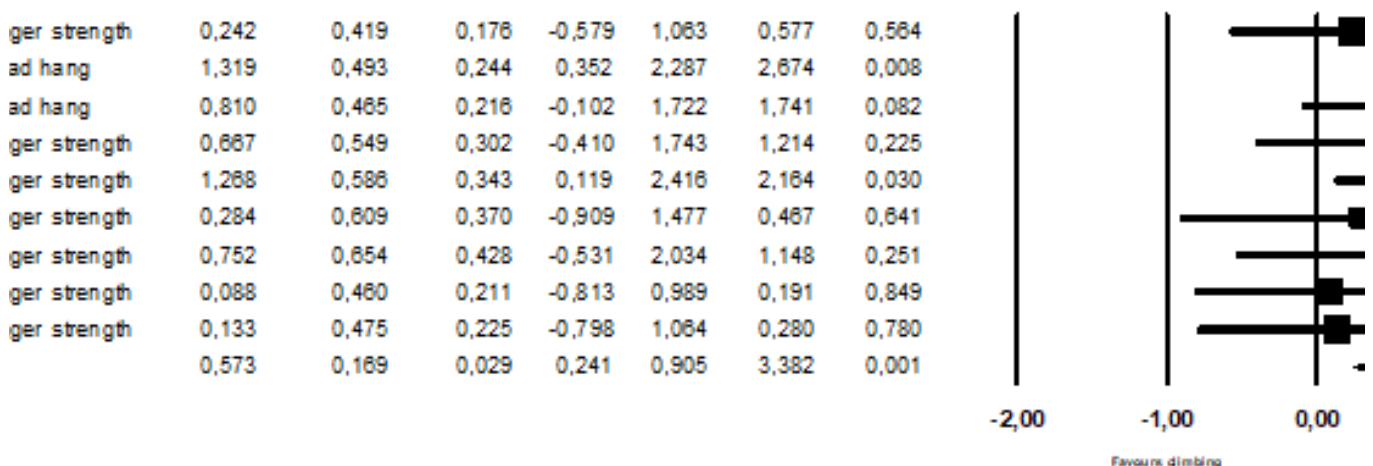


FIG. 2. Main analysis of the effects of climbing specific resistance-training on finger strength and forearm endurance.



FIG. 3. The effect of finger resistance-training on finger strength.

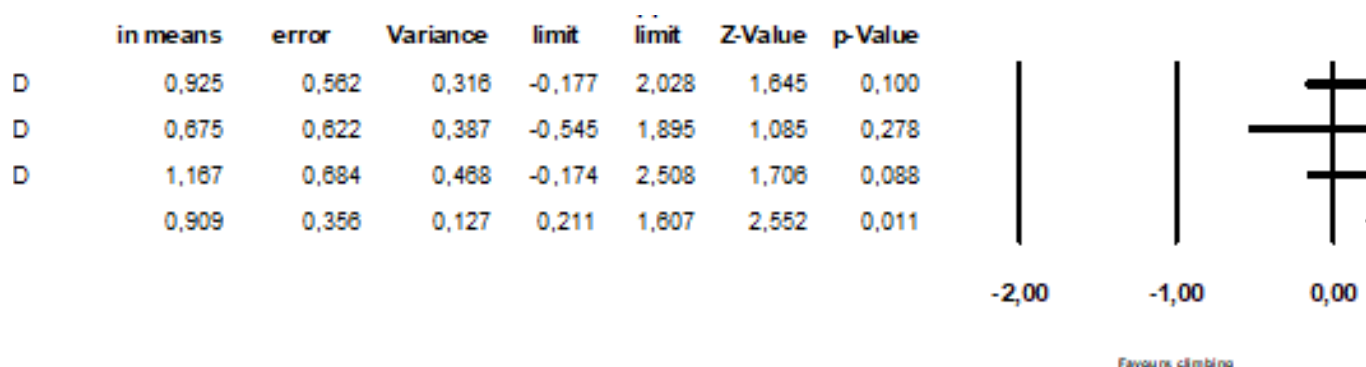


FIG. 4. The effect of finger resistance-training on rate of force development.

on either a 19 mm [34] or 25 mm [35] deep rung was improved by resistance-training of the fingers and forearms compared to climbing training (SDM = 1.23, 95%CI = 0.69–1.77).

Results not included in the meta-analysis

Six of the included studies [26, 36, 37, 39, 40, 43] could not be included in the meta-analysis as they did not include a control group. The findings of these studies are presented below. Further, some results from the studies included in the meta-analysis [27, 33, 35] could not be analysed because the outcomes are presented in only one study and are, therefore, also presented here.

Climbing performance

Five of the studies included in this review measured changes in climbing performance [27, 35, 37, 40]. Although a control group was included in two of these studies [27, 35], the methodological differences (training- and testing-procedures) made it unfeasible to include the results in the meta-analyses. Hermans et al. [35] reported non-significant tendencies toward improved lead climbing

performance following both low-resistance-high-repetitions (12.0%, $p = 0.088$) and high-resistance-few-repetitions (11.3%, $p = 0.090$) upper body resistance-training (e.g., pull-downs, biceps curl, and forearm curl). Neither training modality was superior to the other ($p = 0.420$ – 0.950). Philippe et al. [40] compared the effects of climbing-specific muscular endurance training (combination of hard and easy lead climbing) and muscular hypertrophy training (bouldering, campus board, and hard lead climbing). Both groups improved on-sight lead climbing performance ($p < 0.001$), but the improvements were not different between the groups ($p = 0.542$ – 0.955). Campus board training was also implemented in a study by Stien and colleagues [27] in which two training frequencies (two and four weekly sessions) were compared to an active control group. No significant difference between the two training groups was found, but only the group that trained two times per week improved bouldering performance more than the control group. Moreover, Medernach et al. [37] reported significantly greater improvements ($p = 0.004$) in climbing time to exhaustion following interval bouldering (36.2 ± 14.1 seconds, $p < 0.001$), compared to conventional

bouldering (6.1 ± 19.3 seconds, $p = 0.298$). Finally, Stien and colleagues [26] displayed no within- or between-groups differences following five weeks of lead- or boulder climbing training.

Finger strength

López-Rivera and González-Badillo [39] reported no significant improvements in finger grip strength following four weeks isolated finger resistance-training (2.1–9.6%). The non-significant change in force was significantly greater following dead hang training using maximal external load on a deep rung compared to dead hang training using no external load and the shallowest rung possible in the training. Moreover, Stien *et al.* [26] reported an increase in isolated finger strength following five weeks of bouldering training ($ES = 0.35$, $p = 0.030$), but not lead-climbing training. Importantly, the two studies are difficult to compare due to differences in both training and testing procedures.

Forearm endurance

López-Riviera and González-Badillo [43] demonstrated that forearm endurance improved after four weeks of implementing intermittent dead hangs (25.2%, $p = 0.004$), and not after maximal weighted dead hangs or a combination of the two. López-Riviera and González-Badillo [39] found no change in dead hang endurance following minimal edge or maximal weighted dead hangs, whereas Medernach *et al.* [37] observed improved intermittent finger hang time following interval bouldering (27.3 ± 18.4 seconds, $p < 0.001$), but not conventional bouldering (4.9 ± 11.5 seconds, $p = 0.168$). The intermittent finger hang time improvement was significantly greater following interval bouldering ($p < 0.001$). Similarly, Stien *et al.* [26] found no changes in intermittent forearm endurance following conventional bouldering training, but did report an increased forearm endurance following lead-climbing training ($ES = 0.55$, $p = 0.014$).

DISCUSSION

To the authors' knowledge, this is the first systematic review and meta-analysis examining the effects of different climbing- and resistance-training interventions on climbing performance and climbing-specific muscle strength and -endurance. The main findings from this meta-analysis were that climbing-specific finger endurance was significantly improved following forearm resistance-training [35] and isolated finger training [34], with isolated finger resistance-training improving finger strength more than climbing training alone [33, 34].

Quality scores of the included studies

Of the studies discovered in the systematic search, eleven met all the inclusion criteria. The scores on the PEDro scale for the included studies ranged from 5 to 7 (median = 6) on the 10-point scale, and five RCTs could be included in the meta-analysis. The relatively low sample size provides low statistical power, and although the sample size in this systematic review and meta-analysis is larger than in all individual studies, the results should be interpreted

with caution. Moreover, the need for more high-quality studies in the field of climbing-performance is evident. Specifically, none of the studies utilized blinding of the participants or researchers, and none of the interventions with one or more drop-outs conducted intention-to-treat analyses.

Meta-analyses

The included studies reporting on finger strength [25,27, 33, 34] examined highly trained climbers ($IRCRA \geq 18$). A small-to-medium effect was observed for finger strength after a four-to-five-week finger resistance-training intervention and the improvements could be interpreted as meaningful due to the high performance level and long climbing experience (≥ 4 years) of the included climbers. Moreover, considering the short duration of the interventions, finger- and campus-board training appears to be highly effective training methods that climbers can be implemented in a short training block to emphasize finger strength before competitions. The findings could be explained by the fact that such training prioritizes the finger flexors intensely in a structured and specific training program, whereas climbing training may provide a more varied approach that also trains, and is limited by, other muscles and skills. Finally, marked improvements in finger strength following isolated resistance-training of the finger flexors may be explained by the principle of specificity [44].

Three trials from two studies including only male climbers performing on an advanced-to-international level were included in the meta-analysis of RFD [27, 33]. Stien *et al.* [27] investigated the effects of campus board training performed either two or four times per week with an equated volume. The authors reported that four, but not two weekly sessions improved RFD more than the control group. In the study by Levernier and colleagues [33], the authors examined the effect of fingerboard in top world-ranking climbers and found that a four-week intervention improved unilateral finger flexor RFD more than continuing climbing training as usual. Although the two studies differ in study population, training intervention, and testing methods, it should be of interest that a short training intervention (4–5 weeks) of supplemental resistance training seems able to improve RFD (which is arguably among the strongest predictors of climbing performance [14, 45]) in highly trained climbers. In fact, the studies demonstrated large effects ($SMD = 0.90$) for improvements in RFD compared to climbing as usual. Importantly, only a small number of highly trained, male climbers were included in the studies and the findings may not be generalizable to other populations.

The two studies reporting forearm endurance [34, 35] included in the stratified analysis comprised young climbers (age: ~ 23 –26 years) on a lower grade and intermediate level [35], and highly advanced boulderers [34]. Both studies reported improved forearm endurance following two different approaches to the training. Still, the difference in the study samples makes comparisons of the two studies difficult and challenges the validity of this analysis.

The forearm endurance training in the study by Hermans et al. [35] consisted of forearm curls using a dumbbell, which is not an exercise commonly implemented among climbers and may lack specificity toward the endurance test performed on a shallow rung. One can speculate that the low performance level of the climbers allowed for a non-specific training method to produce significant improvements in the forearm endurance test. Medernach et al. [34] implemented four weeks of resistance-training of the fingers using a shallow rung which is a more specific training method, both for the dead hang endurance test and for climbing. The high specificity toward the dead hang endurance test is probably why this method proved efficient among the highly advanced boulderers included in the study following a short intervention.

Systematic review

The trials that could not be included in the meta-analysis due to no comparison with a control group or the existence of no comparable trials, were included in the systematic review [26, 33, 35–40, 46]. Interestingly, and in contrast to the meta-analysis, most of these studies did not demonstrate significant improvements in forearm endurance or finger strength [38, 39], likely due to the elite performance level of the participants and the low sample sizes. In line with this speculation, the studies included in the meta-analysis [33–35] examined a higher number of climbers performing on a wide range of levels, which could potentially allow potential changes to be more easily detected. However, one study included in the systematic review [26] reported improved finger strength and endurance following bouldering and lead climbing, respectively. The difference could be explained by the intermediate performance level of the participants in the latter study. It should be noted that the generalizability of the individual articles included in this study is limited by the small study samples and varying performance levels and disciplines between studies. The results of both the individual studies and this systematic review must, therefore, be interpreted with caution.

The core has been described as a crucial factor for transferring force throughout the body [47] and core strength has been identified as a secondary determinant of climbing performance after shoulder-strength and -power [48]. One study examined the effect of dynamic or isometric core strength training in climbers [36] and reported improvements in climbing-specific tests (e.g., body lock-off and body-lift), but no significant between-groups differences. Importantly, climbing performance was not tested in the study. Interestingly, Muehlbauer and colleagues [49] found that MVIC of the trunk flexors improved among non-climbers following eight weeks of two weekly indoor climbing sessions. Furthermore, Hermans et al. [35] implemented general upper body resistance-training and found no changes in climbing performance following low or high numbers of repetitions using high or low loads on climbing performance. With a performance level ranging from lower-grade to intermediate, it is possible that the climbers could benefit more from specific climbing training than from general

resistance-training. However, cross-sectional studies have highlighted the importance of shoulder power [48] and elbow flexor strength [50] for climbing performance. Hence, it can be speculated that implementing a similar intervention among more accomplished climbers and using a larger sample size could demonstrate positive effects on climbing performance.

Study characteristics

Most of the intervention studies [25–27, 33, 34, 37–40] were of short duration (four to eight weeks) and the two longest studies lasted no more than ten weeks [35, 36]. Moreover, these were the only two studies that did not include climbing-specific finger resistance-training or changed the climbing routines of the participants in the intervention. Further, two of the studies that lasted eight weeks compared two groups performing very similar training programs: intermittent vs. maximal weighted dead-hangs [43] or endurance vs. hypertrophy training) [40]. The same was true for two of the studies with four-week interventions which also compared two similar training approaches: minimal edge vs. maximal weighted dead-hangs or [39] interval bouldering vs. conventional bouldering [37]. This leaves three studies [25, 33, 34] that were able to identify possible effects of climbing-specific resistance-training of the fingers compared to the effects of continuing climbing training as usual. Importantly, short interventions are not necessarily a limitation in climbing-research. Four weeks is a common duration of blocks in resistance training [51] and as specific finger strength and endurance training involves very high intensity training on small muscles, periodization in four-week blocks is likely a reasonable method for avoiding overuse injuries.

Regarding gender, female climbers are underrepresented in the literature and no interventional studies have included only females. Five studies included in this systematic review and meta-analysis included only males, whereas the remaining seven combined males and females. Hermans et al. [35] did not report the distribution of males and females, while the remaining studies [25, 26, 36, 38–40] had a majority of males (total: 100 males and 45 females). A difference in strength and hypertrophy between men and women with identical training background has been identified [52]. However, it has also been shown that physically active males and females respond similarly in the first weeks (up to 12 weeks) of high-intensity resistance-training programs [53, 54]. Although males and females may respond similarly to climbing-specific resistance-training, the distinct effects on female climbers are yet unknown and should be investigated in future research.

Limitations

As the field of research examining climbing-specific resistance-training is relatively young and only very few interventional studies have been conducted, it can be speculated that comparisons of slightly different training methods are premature. At this point, interventional studies on climbers should rather identify the effects of

training than compare different but relatively similar methods. For example, the effects of two [39] or three [38] highly similar finger resistance-training modalities have been compared and revealed few or no differences in effect. Hence, resources could be better spent comparing the effects to a control group, rather than to a training group performing resembling training programs. Many of the interventional studies performed on climbers comprise relatively few participants, but by performing a meta-analysis we increased the statistical power to detect differences compared to the statistical power in the individual original studies. However, low sample size in studies/comparisons included in meta-analyses, as in the present study, may introduce sparse data bias in the standardized difference in mean [55]. Thus, the standardized difference in mean and its confidence intervals should be interpreted with caution. All meta-analyses indicated no heterogeneity ($I^2 = 0$), but I^2 has substantial bias when the number of studies in a meta-analysis is low and the number of studies/comparisons in our meta-analysis ranged from three to nine, and if the true heterogeneity is high the heterogeneity will be underestimated [56]. The I^2 values in the present study should therefore also be interpreted with caution. Four out of five studies included in the meta-analysis did not include an adequate number of participants to obtain an $\alpha = 0.05$ and a $\beta = 0.2$ which indicates that the included studies were under-powered. Another limitation is that differences in performance level of the study populations (ranging from lower-grade lead climbers to highly advanced boulder climbers) challenge the comparability between studies. Furthermore, the present study is limited by the fact that only three of the included papers [34, 37, 40] received a PEDro score that met the criteria for high-quality studies (≥ 6). One inherent limitation of training studies is the difficulty in blinding of researchers and participants. However, researchers examining climbers should strive to avoid reporting bias in future studies. Finally, as only studies published in English were included, it is possible that papers written in other languages contain further information not included in this systematic review and meta-analysis.

Recommendations for future studies

This systematic review with meta-analysis provides an overview of the current knowledge of the effects of different training approaches on climbing performance and performance in climbing-specific tests. An important finding was the scarcity of scientific, longitudinal literature. Moreover, only three interventional studies could be included in the meta-analysis, due to many studies not including a control group, but rather a secondary training intervention. Hence, it is recommended that upcoming interventional studies include a control

group to explicitly target the effects of the intervention compared to not changing the training routines of climbers. Further, female climbers are underrepresented in the literature and no study has yet examined the effects of climbing or climbing-specific training among only females. Another recommendation based on the current findings is for future research to examine the long-term effects of training interventions in climbers. Thus far, no study has had a duration longer than ten weeks, with most interventions lasting from four to eight weeks. From a practical point of view, future studies should include a measure of climbing performance if possible. Although performance in climbing-specific tests is an indicator of climbing performance, the underlying aim of most research in the field is to explore how climbing performance can be improved. Importantly, this is a highly difficult measure to conduct due to the high complexity of the sport. Still, novel tools such as the Kilter board may present the possibility of including reproducible measurements of climbing performance in future research. Finally, as previously recommended [7], studies should clearly describe their study population regarding preferred discipline, weekly training and climbing volume, performance level, climbing experience and potential block periodization implemented in their regular training routines.

CONCLUSIONS

To our best knowledge, this was the first systematic review and meta-analysis examining the longitudinal effects of climbing and climbing-specific resistance-training on climbing performance and performance in climbing-specific tests. Although the field of climbing research is still in its infancy, some conclusions can be drawn from the available literature. For climbers, it is evident that the addition of systematic resistance-training (e.g., fingerboard, campusboard, or upper-body resistance training) can yield greater improvements in climbing-specific fitness than climbing-training alone, across several performance levels. However, the scarcity of studies limits the possibility of recommending specific training methods. Hopefully, this systematic review and meta-analysis can assist researchers in designing future intervention studies focused on climbers. Specifically, there is a need for 1) studies comparing training to a control condition, 2) studies including only female climbers, and 3) studies that more clearly describe the participants to allow for more precise comparisons and discussions of findings across studies.

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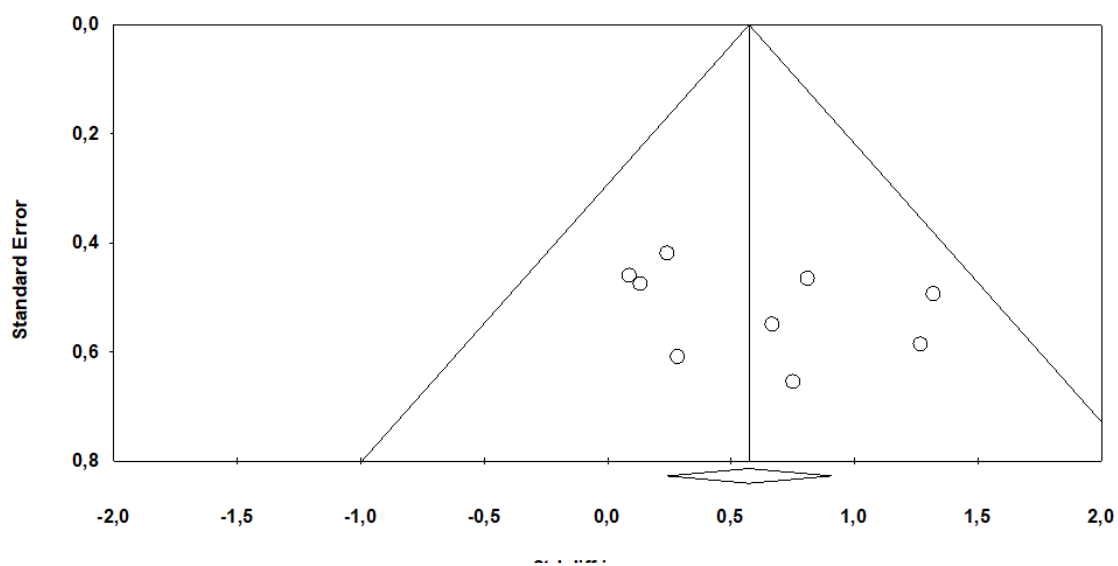
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SUPPLEMENTARY MATERIAL



Supplementary figure 1. Funnel plot of the effect of finger resistance-training on finger strength. The plot indicates no proclivity for publishing studies that found a significant effect of training.

Effect of 4 weeks of plyometric training in the pre-competitive period on volleyball athletes' performance

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ABSTRACT: We aimed to evaluate the effect of 4 weeks of plyometric training (PT), performed in the pre-competitive period, on the vertical jump performance of professional volleyball athletes. We recruited 17 professional female volleyball players (age: 19 ± 3 years; weight: 67.2 ± 5.50 kg; height: 1.81 ± 0.22 m; body fat: $14.4 \pm 2.12\%$; squat 1RM test: 75.5 ± 7.82 kg; training time experience: 6.2 ± 3.4 years) to participate in four weeks of training and assessments. They were divided into an experimental group (EG = 9) and a control group (CG = 8). Both groups were submitted to friendly matches, technical, tactical and resistance training (4 weeks/~9 sessions per week), and internal load monitoring was carried out. The EG performed PT twice a week. At the beginning and end of the four weeks, jump tests were performed. The main findings are: 1) PT when incorporated into the pre-competitive period can induce greater improvements in jumping performance (EG = 28.93 ± 3.24 cm to 31.67 ± 3.39 cm; CG = 27.91 ± 4.64 cm to 28.97 ± 4.58 cm; when comparing the percentage delta, we found a difference between groups with ES of 1.04 and $P = 0.02$); 2) this result is observed when the training load is similar between groups and increases over the weeks, respecting the linear progression principle. Therefore, including plyometric training in the preparatory period for volleyball, with low monotony and training strain increment, is an effective strategy for further CMJ performance improvement.

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INTRODUCTION

Different training methods are applied across the training periods in a periodization [1]. In the pre-competitive period, there is a predominance of high training volume. As the training progresses, the volume is decreased and the intensity is increased [1]. Therefore, power training, such as plyometrics, is generally included in the competitive training period [2]. This logical and linear sequence, represented by the decrease in volume and increase in intensity, is applied to reduce the chance of concurrent training [1, 3]. However, the short time of the pre-competitive period and the most frequent game schedule [3] mean that volleyball athletes need to improve their jumping performance from the pre-competitive period on [4].

The motor pattern of countermovement jump (CMJ) movements is essential to serve, block and attack in volleyball [5], as well as for performance assessment [6, 7]. Thus, using jumps at specific periods in a season (such as the pre-competitive period) can help physical trainers and coaches to quantify the training programme efficacy

performance improvement [8]. To improve jumping performance, plyometric training (PT) (exercises that are characterized by a rapid transition between the eccentric and concentric phases, generating greater accumulation of elastic energy) [2, 9] is a valid method [4, 10, 11]. However, there are still gaps in the literature regarding the efficacy of PT applied in the pre-competitive period and whether it promotes the concurrent effect.

The internal and external training load monitoring must be controlled for performance improvement [5, 12–14]. Training monitoring through rating of perceived exertion (RPE) and session duration (in minutes) is an effective and inexpensive way to quantify the training impulse [15]. The session's RPE, total weekly training load (TWTL), monotony and training strain are examples of these variables [5, 12, 14]. Here we evaluate whether the inclusion of plyometric training during the pre-competitive period has a concurrent effect with technical and tactical training, friendly matches and

resistance training or if it contributes to the jump performance improvement.

Therefore, the aim of the present study was to evaluate the effect of 4 weeks of PT, performed in the pre-competitive period, on the jump performance of the professional female volleyball athletes.

MATERIALS AND METHODS

Study design

The sample consisted of 17 female players ([mean $\pm$ SD] age: 19.5 ± 3.73 years; weight: 67.2 ± 5.50 kg; height: 1.81 ± 0.22 m; body fat: $14.2 \pm 2.53\%$; 1RM test: 75.5 ± 7.82 kg; training time: 6.2 ± 3.4 years), randomly divided into an experimental group (EG): $n = 9$ and a control (CG): $n = 8$ (with practically the same number of athletes per position within each group), belonging to a Brazilian professional club, participating in Superliga B, in the year 2018. The evaluations were carried out in 4 days of non-consecutive tests. The first visit to the laboratory was for familiarization with the maximum repetition test (1RM), CMJ, RPE scale and training protocols, randomization and anthropometric data collection. After 48 hours, the second visit was for the 1RM test. Again, after 48 hours, the third visit was for the pre-intervention CMJ test. Between the third and fourth visits to the laboratory, the EG and CG four-week training programmes were carried out, with the internal load being monitored by the RPE of the session and total training time (expressed in TWTL), monotony and strain. Finally, after four weeks of intervention, the fourth visit was for the

post-intervention CMJ test and anthropometric data. The CMJ tests were performed on Monday morning of the first week of intervention and after the four weeks of intervention. With this procedure, we ensure that athletes come from a more extended period of rest to the detriment of the weekend. All athletes were already familiarized with the instruments used in the research.

The volunteers were informed about the purpose of the study and signed the Informed Consent Form following the recommendations of Resolution 466/12 of the National Health Council. The Research Ethics Committee approved the study.

Training protocol

The study was carried out within the pre-competitive period and lasted for four weeks. The mesocycle schedule consisted of technical/tactical training sessions, friendly games and resistance training (RT), in addition to PT for EG. The distribution of training sessions over the four weeks can be seen in Table 1. The technical/tactical training models were based on the study by Trajkovic [16]. The RT consisted of performing exercises that were already part of the athletes' training routine (an organization aimed at recruiting the whole body, in exercises such as squat with body weight, prone bridge and hip thrust with body weight, adduction and abduction with elastic bands, open row with elastic bands and push-up exercise). Four sets (60 seconds rest) were performed for each exercise with open repetitions/durations. The orientation was for the intensity of each series not to exceed 7 in the RPE and 3 in the total session. The objective of these sessions

TABLE 1. Training sessions distributions in the intervention period.

Day	Period	Week 1–2	Week 3	Week 4
Monday	Morning	CMJ + TTT	TTT	TTT
	Afternoon	TTT	TTT	TTT
Tuesday	Morning	PT(EG)/TTT(CG)	PT(EG)/TTT(CG)	PT(EG)/TTT(CG)
	Afternoon	OFF	OFF	TTT
Wednesday	Morning	RT + TTT	TTT	TTT
	Afternoon	TTT	TTT	TTT
Thursday	Morning	PT(EG)/TTT(CG)	PT(EG)/TTT(CG)	PT(EG)/TTT(CG)
	Afternoon	OFF	OFF	OFF
Friday	Morning	TTT	TTT	TTT
	Afternoon	OFF	TTT	TTT
Saturday	Morning	TTT	OFF	OFF
	Afternoon	OFF	FM	FM
Sunday	Morning	OFF	OFF	OFF
	Afternoon	OFF	OFF	OFF
N sessions		8	9	10

Legend: PT: Plyometric Training; RT: Resistance Training; TTT: Technical/Tactical Training; FM: Friendly Matches; CMJ: countermovement jump Test; EG: Experimental Group; CG: Control Group.

was to maintain the general conditioning already proposed in the two previous weeks. For both groups, given the specificities of each position in tactical and technical training, similar total training loads (external load) were applied and the internal load was recorded. PT sessions for the EG were held while the CG performed technical and tactical training. Before all training sessions, the two groups completed a warm-up for approximately ten minutes consisting of light running, dynamic stretches, and general movements.

Two weeks before the intervention, the players underwent technical/tactical, aerobic, strength-endurance, balance, and flexibility training, in addition to neuromuscular assessments. The aim of those two weeks was to improve the general conditioning of all players as well as to avoid injuries [1, 16]. The internal load monitoring (expressed in TWTL) from this period was also recorded and classified as having moderate-low magnitudes (≥ 1257 to < 2514 arbitrary units [AU]) for both groups [12].

Plyometric training protocol

The PT protocol consisted of 8 sets of jumps per session, with and without additional load, being: initially, four sets of 10 consecutive maximum jumps, with additional load coming from a bar positioned in the cervical region (specificity of the squat exercise), with 20% of RM. Soon after, there were 4 sets of 15 seconds each (adapted from Hespanhol, Silva Neto, and Arruda [17] of maximum consecutive jumps, without additional load and applying the CMJ pattern. The pattern of movement, for both the jumps with and without additional load, was from crouching to approximately 90° of knee flexion. For jumps with the additional load, the hands should stabilize and keep the bar resting on the cervix. Between sets and exercises, a rest interval of 90 to 120 seconds was applied. For all jumps, experienced evaluators verbally encouraged and gave feedback to the athletes about the movement pattern. In all PT sessions, all athletes were able to perform 10 jumps in the 4 sets with additional load and also maintain the CMJ movement pattern in the 4 sets of 15 seconds each. As they are professional athletes, they already had experience in plyometric training, which justifies the choice of PT.

Research tools

Anthropometry

To characterize the sample, we determined the height and body mass of the subjects, using a scale that had a stadiometer (110 FF, Welmy, Santa Bárbara d'Oeste, Brazil). The fat percentage was estimated using a bioimpedance device (Quantum BIA-II, RJL Systems, Clinton Township, USA). Tetrapolar electrodes were used for collection (Bio Tetric, Sanny, São Bernardo do Campo, Brazil).

1RM test

The 1RM test was performed through the half squat exercise (approximately 90° of knee flexion in eccentric/concentric transition action). Initially, the participants performed a general warm-up, followed by performing a specific warm-up set that consisted of

8 repetitions at approximately 50% of the estimated 1-RM. Then they performed another series of 3 repetitions at 70% of the estimated 1-RM. After 5 minutes of recovery, load increments were applied until failure. The number of single series did not exceed 5 attempts. The rest interval between sets was 5 minutes [18]. During the test, the cadence of movement was controlled using a digital metronome (DM90, Seiko, Tokyo, Japan), with 2 seconds for the eccentric phase and 2 seconds for the concentric phase.

Internal load monitoring

The session RPE scale, monotony and training strain were measured to control the internal load [15]. Athletes assessed psychophysiological stress through the RPE session. This value was multiplied by the duration of the training session, in minutes, and this final product represented the training load of the session (value in AU). The procedure was performed 20 to 30 minutes after each training session, for each athlete, being asked: "How was your training today?" The TWTL (sum of the loads of each training session in the weeks) the monotony (average of the training loads of the sessions weekly divided by their standard deviation) and strain (multiplication of monotony by the sum of training loads accumulated in the week) [15] were used for the analyses.

Countermovement jump assessment (CMJ)

The participants were subjected to the CMJ test to measure the jump height performance at different times [19], using a contact platform (Cefise, Brazil) interconnected to the software (Jump System, 1.0, Brazil) [14, 20]. Before the jumps, each athlete performed a standardized 5-minute warm-up consisting of general movements and dynamic stretching. To perform the jumps, the hands were on the hips and participants were previously instructed to squat at approximately 90° of knee flexion, jump as high as possible and keep the legs straight in the flight phase. Athletes performed three vertical jumps with a 5-second rest interval between attempts. The mean value of the three attempts of CMJ was used for analysis [21]. The coefficient of variation (%) of the CMJ was 1.1 for the EG before and after intervention; 1.7 for the CG before intervention and 1.6 after intervention.

Statistics

ANOVA for repeated measures was applied to compare TWTL, monotony and strain through the weeks. We checked the data sphericity through Mauchly's test, and when appropriate a Greenhouse-Geisser correction was made. One-way analysis of variance (ANOVA) testing was used to compare groups at baseline for CMJ; if the F-statistic test showed a significant difference, the Bonferroni post-hoc test was applied to show the direction of the difference, but it was not necessary. The delta comparison for CMJ between groups was made through the independent t-test, and the effect size was calculated through Hedge's g. We applied the dependent t-test to compare body mass and percentage of body fat within groups before and after 4 weeks of training. The assumption of the equality of variances was confirmed

by examination of Levene's test and normality through the Shapiro-Wilk test. The between-group difference of the change in continuous variables from baseline to 4 weeks was assessed through analysis of covariance (ANCOVA), with the week four values as the dependent variables and the baseline value as a covariate and, where appropriate, a post-hoc analysis with a comparison of main effects and a Bonferroni adjustment. Following the ANCOVA analyses the Cohen's *d* test was applied to evaluate the effect size (ES) of CMJ before and after treatment. Cohen's categories used to assess the magnitude of ES were: (small if $0 \leq [g] \leq 0.50$; medium if $0.50 < [g] \leq 0.80$; and large if $[g] > 0.80$). The level of significance adopted for the analyses was $p \leq 0.05$. The smallest worthwhile change (SWC) was set by using Cohen's principles for a small ES (i.e., 0.2) for each variable tested [22]. We conducted all analysis through JASP 0.9.2.

RESULTS

Table 2 shows the body composition of both groups at the beginning and end of the intervention, showing that there are no significant changes in any variable.

Figure 1 shows the comparisons of the within- and between-group CMJ at the pre- and post-intervention time points. The values of both groups were as follows: the EG showed an increase from

28.93 ± 3.24 cm to 31.67 ± 3.39 cm between the pre- and post-intervention measurement; the CG recorded an increase from 27.91 ± 4.64 cm to 28.97 ± 4.58 cm between the pre- and post-intervention assessment. The analysis of covariance, considering the pre-test CMJ as a covariable, found a difference between the groups for the post-training measurement (ES: 0.43; $P = 0.027$) with an average difference between groups of 1.74 cm. For the baseline treatment, no differences were found between groups (ES: 0.25; $P = 0.60$) with an average difference between groups of 1.02 cm.

Athletes should increase the jump height by 0.77 cm (2.72%) as estimated by SWC analyses. From Figure 2, we can see that two athletes (22.2%) from the EG and three athletes (37.5%) from the CG had no significant improvement at the end of the preparatory period. The improvement of all athletes is possibly due to the internal load, monotony, and strain being within expected. However, the EG had a more considerable improvement than the CG, showing the importance of including plyometric training at this stage of training. In the graph below, grey is the EG and black is the CG. The dotted line is the SWC (2.72%).

When comparing the percentage delta, we found a difference between groups (EG: $9.77 \pm 2.34\%$ and CG: $3.94 \pm 0.71\%$) with ES of 1.04 and $P = 0.02$ (Figure 3).

TABLE 2. Comparison of anthropometric data between the pre and post groups.

Variables	Experimental Group (n = 9)				Control Group (n = 8)			
	Pre Training	Post Training	<i>p</i>	E.S.	Pre Training	Post Training	<i>p</i>	E.S.
Body Mass (kg)	67.7 ± 4.32	67.5 ± 4.77	0.54	-0.04	66.9 ± 6.35	66.6 ± 5.48	0.78	-0.05
Body Fat (%)	14.4 ± 2.12	14.2 ± 1.85	0.87	-0.10	14.1 ± 2.75	14.0 ± 1.98	0.85	-0.04
Height (m)	1.80 ± 0.30	–	–	–	1.82 ± 0.21	–	–	–

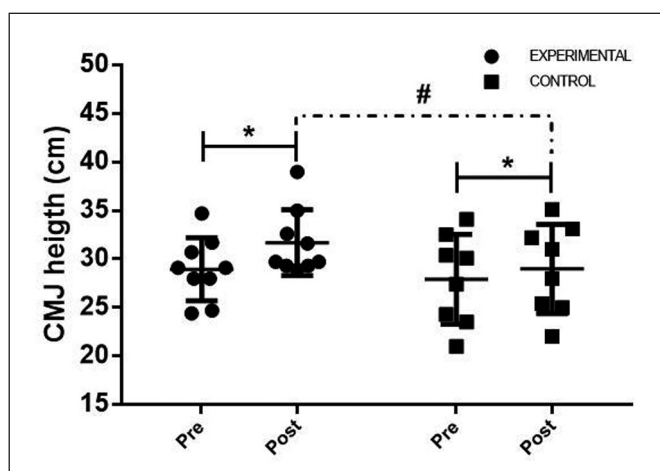


FIG. 1. Comparison of the Countermovement Jump between and within groups * Difference between-group pre- and post-intervention moments: $p \leq 0.05$; # Difference within-group pre- and post-intervention moments: $p \leq 0.05$.

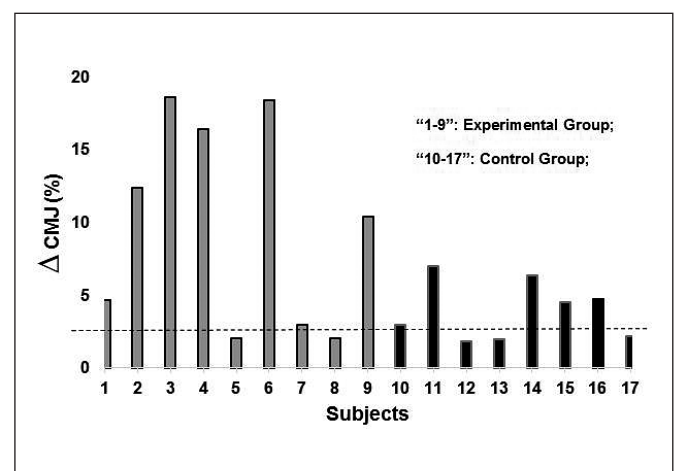


FIG. 2. Individual plots and smallest worthwhile change of the gain values in the Countermovement Jump.

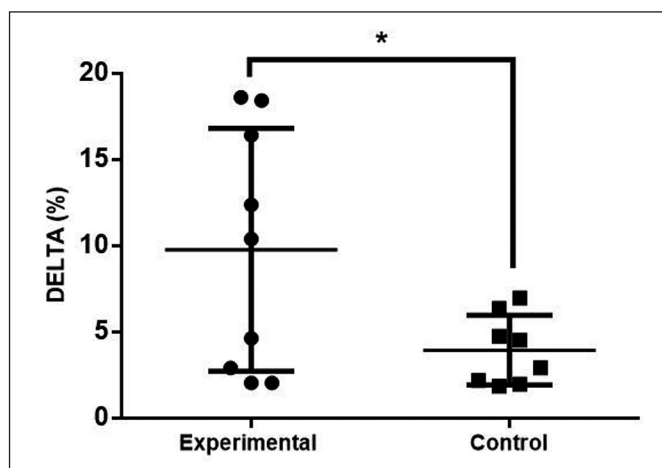


FIG. 3. Comparison of the percentage delta Countermovement Jump between groups * Difference between-group: $p \leq 0.05$.

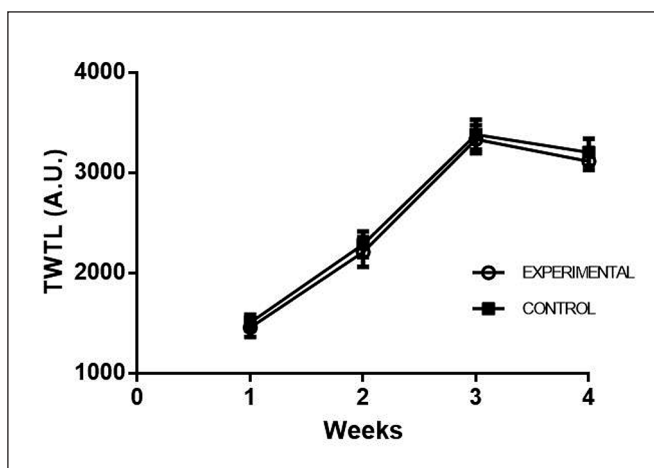


FIG. 4. Comparison of the Total Weekly Training Load (TWTL) within and between groups during the four weeks.

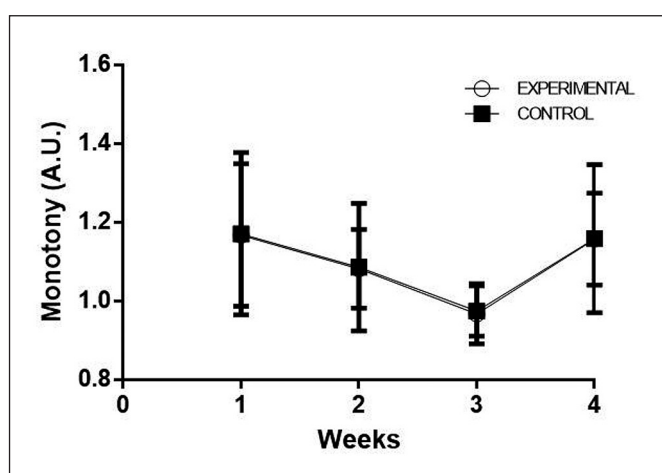


FIG. 5. Comparison of the Monotony within and between groups during the four weeks.

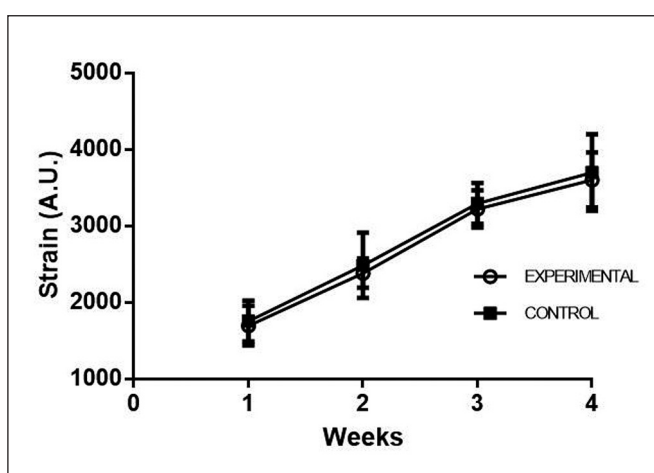


FIG. 6. Comparison of the Strain within and between groups during the four weeks.

Figure 4 shows the results of TWTL within and between the EG and CG during the 4 weeks of training. TWTL was not different between groups within each week. For EG, week 1 had lower TWTL than weeks 2 (ES: -3.01), 3 (ES: -7.52) and 4 (ES: -6.63) ($P < 0.001$). Week 2 had lower TWTL than weeks 3 (ES: -4.50) and 4 (ES: -3.62) ($P < 0.001$). Week 3 had higher TWTL than week 4 (ES: 0.88; $P = 0.019$). The CG had a similar response, with week 1 having lower TWTL than weeks 2 (ES: -2.94), 3 (ES: -7.07) and 4 (ES: -6.40) ($P < 0.001$). Week 2 had lower TWTL than weeks 3 (ES: -4.13) and 4 (ES: -3.46) ($P < 0.001$). Week 3 had higher TWTL than week 4 (ES: 0.66; $P = 0.25$).

As shown in Figure 5, a decrease in monotony was observed with the training progression. Week 3 of the CG had less monotony than week 1 (ES: 0.855; $P = 0.028$) and week 4 (ES: -0.80; $P = 0.053$). The same was observed for EG (ES: 0.924; $P = 0.012$ and ES: -0.878; $P = 0.021$).

Finally, Figure 6 shows how the strain increased with the training progression. There was no difference between groups. Within the groups, the only time when there was no difference was between weeks 3 and 4.

DISCUSSION

Our main findings showed that both groups improved their CMJ performance at the end of the intervention period. However, the EG achieved better results than the CG, both in values of percentage delta ($P = 0.02$ and ES of 1.042) and CMJ height ($P = 0.027$ and ES of 0.43), as well as according to the analysis of individual data and SWC (22.2% (EG) versus 37.5% (CG) of the athletes did not improve what they could have improved according to the SWC values (0.77 cm or 2.72%). One of the initial hypotheses was that both groups could improve the CMJ performance because they were at the beginning of the season. However, there was uncertainty as regards

the amount of improvement each group would achieve and whether the PT of just 4 weeks, spread over 8 sessions, would provide a more substantial effect than technical and tactical training only. Our data show that the increase in PT incorporated into the specific volleyball training in the pre-competitive period brought greater benefits to the performance of the athletes in the EG than the CG.

Another critical point to be discussed was the initial equalizations between the groups for the CMJ performance, the internal load monitoring throughout the intervention and the lack of change in body composition during the intervention as well. Such mechanisms allow us to affirm that the greatest gain obtained by the EG came from the plyometric training incorporation. It is worth mentioning that all athletes who started the study ended without any injury.

For performance variables such as the CMJ to be faithfully assessed and compared in specific periods and between groups, it is necessary to monitor the internal load. The relationship between what was proposed by the physical trainer (external load) and what was reported by athletes (internal load) was expressed in data from TWTL, monotony, and strain [5, 12, 14, 23]. Training strain data report a progression of the load over 4 weeks. Also, a monotony threshold with a value of 2.0 is proposed [24, 25], with values above that presenting a higher risk for overreaching and performance decrement. In any of the weeks the threshold value was reached for any group; a study [12] reported values of up to 1.6 for monotony, 8000 AU for strain and 4500 for TWTL in the pre-competitive period for professional volleyball players from the main Brazilian league. Thus, the data of the internal load monitoring obtained further confirm that the distribution of the external training load in the present study was suitable.

The plyometric training protocol proposed in our study suggests a load of 20% of the RM and consecutive jumps, added to an evaluation protocol proposed elsewhere [19]. Studies using the squat jump with an additional load to improve lower limb power in athletes are found in the literature [26–28]. However, they used different methodologies and adaptive physiological mechanisms from ours. Such studies propose jumping training based on the hysteresis mechanism [29], which benefits the action of the active or contractile components of the neuromuscular system. Thus, the methodology proposed here was not found in the literature, making it an efficient, applicable and unprecedented tool.

The neural and mechanical adaptations coming from the PT and achieved by the EG were in a higher magnitude than the CG. The stretching-shortening cycle is one of the primary adaptations promoted by PT and could explain athletes' improvement in performance, through the increased muscle-tendon junction stiffness [2] and better use of elastic components [30]. Also, mechanoreceptors such as muscle spindles and Golgi tendon organs are sensitive to PT. The first one undergoes adaptations of higher stimulation [31] and the second one undergoes adaptations of inhibition [32]. This combination could provide the jump performance improvement. Consequently, intermuscular coordination and

motoneuron firing frequency establish a more acute adaptive form, thus helping to improve performance. Although these described adaptations are speculative (we did not evaluate them directly, which therefore constitutes a limitation of the study), we must pay attention to some details. As they are professional athletes with great experience in performing the CMJ test (proved by the low coefficient of variation), the maintenance of the motor pattern at all times can be verified. Thus, this variable did not interfere with the results obtained. Furthermore, based on Figure 2, we can see that all athletes improved their jump height. However, the individual variation within and between groups (assessed by the SWC), even the athletes being in the same phase of the season and being randomly allocated to each group, seems to demonstrate that experienced athletes (in the pre-competitive period and lasting only 4 weeks of training) benefit in greater magnitude from the PT, which is the cause of the greatest improvement in the EG.

The short time of 4 weeks seems to offer different responses to training. Mazurek *et al.* [33] found no differences in CMJ height over 5 weeks for a group of handball players who performed PT twice a week. However, Debien *et al.* [12] verified the difference in the CMJ of professional volleyball players from 2 to 5 weeks in the pre-competition period. Additionally, in a recent study the authors applied the PT over 6 weeks on volleyball players and also observed significant improvements in the CMJ [2]. This CMJ is widely used to measure the players' performance in athletes of different levels, having excellent applicability and reproducibility [34, 35]. The specific jump training that contains sports movements seems to be more useful for performance evaluation [36]. Therefore, the usage and performance values of the CMJ observed here are quite similar to data obtained in another study (~30 cm) with women athletes from the first and second Slovenian and Portuguese volleyball divisions, showing that our findings are consistent with those of the current literature.

Finally, the outcomes from the applied PT in the pre-competitive period reported here increase the inquiries regarding the classic linear periodization. Thus, having established the effectiveness of a PT programme at different periods of the season [2, 4], it is clear that the results obtained from the CMJ performance and also the absence of injury among the assessed players substantially increase the practical applicability of the research. It is clear that the sample size (relatively small), the length of stay in the offseason period (uncontrolled) and the extrapolation of the effects of PT by four weeks for the entire season are limitations of the study. However, coaches and fitness trainers can apply this complementary methodology especially when the season calendar suggests short pre-competition times.

CONCLUSIONS

We conclude that plyometric training, when incorporated into specific volleyball training in the preparatory period, can induce more substantial improvements in jumping performance (~ 10%). This result was observed when the training load was similar between

groups and increased over the weeks, respecting the linear progression principle. Also, we observed a decrease in training monotony over the weeks, and strain increase, which shows that the training was well distributed. Therefore, including plyometric training in the preparatory period for volleyball, with low monotony and training strain increment, is an effective strategy for further CMJ performance improvement.

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Conflict Interest Statement

The experimental work conforms to the highest standards of safety and ethics, and to the laws of the country in which the work took place. The authors state that there is no conflict of interest.

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Analysis of velocity- and power-load relationships of the free-weight back-squat and hexagonal bar deadlift exercises

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ABSTRACT: The aim of this study was to analyse the load-velocity and load-power relationships in the free-weight back-squat (BSQ) and hexagonal bar deadlift (HBD) exercises. Twenty-five ($n = 25$) resistance-trained men (age = 23.7 ± 2.8 years) performed a progressive load test at maximal intended velocity to determine their BSQ and HBD one-repetition maximum (1RM). Mean propulsive velocity (MPV) during the concentric phase of the lift was recorded through a linear encoder. Load-velocity and load-power relationships were analysed by fitting linear regression and the second-order polynomial, respectively, to the data. Maximum strength (1RM), MPV (30–80% 1RM), and power output (30–90% 1RM) were higher for HBD compared to BSQ exercise ($p < 0.05$). A very strong relationship between MPV and relative intensity was found for both BSQ ($R^2 = 0.963$) and HBD ($R^2 = 0.967$) exercises. The load that maximizes power output (P_{max}) was $64.6 \pm 2.9\%$ (BSQ) and $59.6 \pm 1.1\%$ (HBD) 1RM. There was a range of loads at which power output was not different than P_{max} (BSQ: 40–80% 1RM; HBD: 50–70% 1RM). In conclusion, the load-velocity and load-power relationships might assist strength and conditioning coaches to monitor and prescribe exercise intensity in the BSQ and HBD exercises using the velocity-based training approach.

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INTRODUCTION

Exercise intensity is one of the most important variables in resistance training (RT) for increasing muscular strength [1]. The one-repetition maximum (1RM) and the maximum number of repetitions (RMs) are among the main reference parameters used to determine exercise load [1, 2]. Although the direct assessments of 1RM and RMs are considered valid and effective approaches for prescribing exercise loads [3, 4], their use is often associated with some drawbacks which may limit their implementation (e.g., time-consuming and fatiguing procedures and 1RM daily fluctuations) [2, 3, 5].

Velocity-based training (VBT) has been proposed as a feasible alternative to the traditional 1RM-based approach to support the prescription and adjustment of the exercise load in a variety of resistance exercises due to the very strong and stable load-velocity relationships (R^2 range: 0.94 to 0.98) [2, 6–8]. The use of general load-velocity relationship equations enables strength and conditioning coaches to easily determine which relative load (%1RM) is being lifted from the bar velocity recorded during a single repetition performed at maximum effort [2]. These data highlight the need for

further investigation of the entire load-velocity relationship in the most common resistance exercises employed in RT programmes to successfully implement the velocity-based approach.

The back-squat (BSQ) and deadlift exercises and their variations are among the most common resistance exercises used to enhance the strength of knee extensors and flexor muscles [9]. Different exercise modes (Smith machine vs. free-weight, range of motion, and equipment design) produce distinct kinematic outputs and load-velocity relationships [10–13]. For example, previous studies showed that modifying the squatting depth (i.e. full vs. half) resulted in different biomechanical patterns, force development, and kinematic outputs [6, 10]. The load-velocity relationship in the Smith machine BSQ and traditional deadlift (i.e., straight bar) exercises has already been described [8, 10, 14–17]. However, reports of the load-velocity and load-power relationship in variations of the back-squat (i.e. free-weight) and traditional deadlift (i.e., hexagonal bar) exercises are limited.

Despite the popularity of both free-weight BSQ and hexagonal deadlift (HBD) exercises among strength and conditioning coaches,

to the best of the authors' knowledge, no study has compared the kinematic outputs of these exercises. From a mechanical perspective, shifting the load position can alter the kinematics and kinetics in lifting [18–20]. For example, the HBD makes it possible to keep the load closer to the individual's body, reducing the amount of torso inclination and horizontal displacement of the bar, which may provide favourable vertical displacement over the BSQ exercise [18, 20, 21]. From a practical perspective, the resulting equations provided here would enable strength and conditioning coaches to incorporate the VBT paradigm for the free-weight BSQ and HBD exercises in their RT programmes.

Another important application of measuring bar velocity is to determine the range of loads able to maximize power output through the load-power relationship [10, 17], defined as the “optimum power zone” [22]. There is evidence supporting the effectiveness of training in the “optimum power zone” to enhance strength performance [22, 23]. Identifying this range of loads might be useful for strength and conditioning coaches to determine lower and upper limits of loads capable of producing high mechanical power output instead of using a single “optimal load” [22].

Given the above, the aims of this study were: (i) to determine the accuracy of movement velocity to estimate 1RM through the general and individual load-velocity relationship in the free-weight BSQ and HBD exercises; and (ii) to compare the load-velocity and load-power relationship of both exercises in resistance-trained males. Given the very strong load-velocity relationship previously reported [6, 16, 17], it was hypothesized that movement velocity would accurately predict 1RM for both exercises, but the load-velocity and load-power relationships would be exercise-dependent.

MATERIALS AND METHODS

Participants

Twenty-five ($n = 25$) resistance-trained men aged from 18 to 30 years (age = 23.7 ± 2.8 years; weight = 81.3 ± 8.4 kg; height = 1.77 ± 0.1 m) volunteered to participate in this cross-sectional study. All participants had experience in RT of 4.4 ± 1.3 years, with a training frequency of 2–5 RT sessions per week in the last 12 months, and were capable of performing both exercises with proper technique. All participants were free of muscular and joint injuries at the time of the study. The study was approved by the local Ethics Committee following the Declaration of Helsinki. All participants signed an informed consent form.

Study design

Participants were required to attend the training facilities in three visits, with ~ 48 h separating visits 1 and 2, and at least ~ 1 week of rest between visits 2 and 3. The first visit involved the familiarization session (2 sets of 8 and 6 repetitions with 40 and 60 kg for both exercises), and visits 2 and 3 included the direct assessment of 1RM for back-squat and HBD exercises (randomized order) using a linear encoder for collecting mechanical output. Each visit was

preceded by a standardized warm-up (10 min), which included dynamic stretching and joint mobility (3 min), light running (5 min), and a specific back-squat or HBD warm-up set for each exercise (1 set of 8 reps with 40 kg [BSQ] and 43 kg [HBD]), separated by 2 min of recovery. Participants were requested to attend each visit in a well-rested state (i.e., ≥ 8 hours sleep, to maintain their normal dietary habits, and to abstain from any physical exercise and beverages containing alcohol and caffeine ingestion in the 24 h before the sessions). Testing sessions were performed from 2:00 to 6:00 p.m., at the same time of day for each participant (± 1 hour).

Testing procedures

After warming up, subjects rested for 2 min before starting the 1RM test. The initial load was set as 30 kg and 43 kg for the BSQ and HBD exercises, respectively. The load was increased by 20 kg until reaching a mean propulsive velocity (MPV) of $0.8 \text{ m} \cdot \text{s}^{-1}$ and $0.6 \text{ m} \cdot \text{s}^{-1}$ for BSQ and HBD, respectively, followed by increments of 10–5 kg (MPV = $0.8\text{--}0.5 \text{ m} \cdot \text{s}^{-1}$ and $0.6\text{--}0.4 \text{ m} \cdot \text{s}^{-1}$ for BSQ and HBD, respectively), and 5–1 kg up to 1RM. Three repetitions were performed for light (MPV $> 0.8 \text{ m} \cdot \text{s}^{-1}$), two for medium (MPV = $0.5\text{--}0.8 \text{ m} \cdot \text{s}^{-1}$), and one for heavy (MPV $< 0.5 \text{ m} \cdot \text{s}^{-1}$) loads, with an inter-set rest period of 2 min, 3 min, and 4 min, respectively. Each participant received real-time feedback of the bar velocity and verbal encouragement to exert their maximum effort at every repetition. The fastest MPV in each set was recorded for analysis.

The eccentric portion of the movement was executed in a continuous and controlled manner (2–3 s) with a momentary pause (~ 1.5 s) between the eccentric and concentric phases to minimize the contribution of the rebound effect and provide more reliable data for both exercises [24]. The duration of the eccentric and isometric phases was paced by one of the investigators. This had been previously practised in the familiarization session. Ankle plantar flexion was allowed at the end of the movement for the light and moderate loads in both exercises, but without lifting the toes off the ground. If a repetition failed to meet these requirements, the set was discarded and repeated following a 3 min rest. This was visually supervised by one of the investigators examining the proper lifting technique during the test.

The BSQ exercise was performed as previously described [25]. Participants started from an upright position, with knees and hips fully extended, feet approximately shoulder-width apart and pointing slightly outward. The bar was placed in the upper portion of the trapezius muscle. This position was individually adjusted and replicated on every lift. From this position, they were required to flex their knees to $\sim 90^\circ$ (determined by an elastic band placed parallel to the ground by a tripod), then fully extended their lower limbs at the end of lifting. The HBD exercise started with the bar on the floor with the high-handle grip following the previous recommendations [21]. The shoulder should be in line with the handles and hips lower than the shoulders. Stance position should be with feet approximately shoulder-width apart, both pointing slightly outward. From this position,

they were instructed to lift the load and continue standing erect (full-arm-knee-hip extension) with their shoulder retracted for 1.5 s at the end of the lift. The bar was held on the ground for 1.5 s before each lift. No belts or straps were allowed [19].

Measurement equipment and data recording

A linear position transducer (Speed4lifts, Madrid, Spain) was attached to the bar to measure the lifting kinematics. This system measures the cable displacement in response to changes in the bar position during the concentric phase at a sampling rate of 100 Hz [26]. The velocity parameter used in the present study was the MPV (i.e., the portion of the concentric phase in which the measured acceleration [α] is greater than the acceleration due to gravity [$\alpha > -9.81 \text{ m} \cdot \text{s}^{-2}$] [27]. MPV and the weight of the load lifted (bar + weight plate) were considered to calculate the mechanical power output (P) as follows [28]:

$$P = (\text{Load lifted} \cdot g) \cdot \text{MPV}$$

where g is the gravitational acceleration (α), which is equal to $9.81 \text{ m} \cdot \text{s}^{-2}$.

The Speed4Lifts system has been demonstrated valid and reliable to record movement velocity for medium and heavy loads, with the absolute error below the acceptable maximum error criterion ($< 5\%$ of 1RM) [26, 29].

Statistical analysis

We used standard descriptive statistics to calculate the mean, standard deviation (SD), percentage of coefficient of variation (%CV), standard error of the estimation (SEE), and confidence interval (95% CI) of the outcomes. Load-velocity and load-power relationships were analysed by fitting linear and second-order polynomial regression to all data points, respectively. The goodness of fit of the load-velocity and load-power relationships were analysed using the coefficient of determination (R^2) and the 95% CI.

The accuracy of the general load-velocity relationship was obtained using the load closest to 80% 1RM and loads from 30 to 80% 1RM were used to estimate the 1RM from individual load-velocity relationships [16]. We used the minimal velocity threshold as the upper limit of the V1RM obtained from the general load-velocity relationship (i.e., BSQ [$0.31 \text{ m} \cdot \text{s}^{-1}$] and HBD [$0.30 \text{ m} \cdot \text{s}^{-1}$]) to estimate 1RM through the individual load-velocity relationship (Table 1). After determining the %1RM related to the selected load ($\sim 80\%$ 1RM) through the general equation, the following cross-multiplication was used to estimate the 1RM (30):

$$1\text{RM} = \text{Load}(\text{kg}) \times 100 / \%1\text{RM}$$

We used a paired t-test to compare the average MPV values attained with each %1RM between exercises. The agreement between actual and predicted 1RM was assessed by intraclass correlation coefficient analysis, Bland-Altman plots and their 95% limits of agreement. A two-way (exercise $\times$ load) ANOVA was used to compare the

mechanical power output at different loads (i.e., %1RM and percentage of body mass). Bonferroni's post-hoc analysis was used to identify the significant differences. The analysis was performed in SPSS (IBM Corporation, New York, USA). The significance level was set at 5%.

RESULTS

The 1RM for the 25 participants included in this study was $123.20 \pm 13.63 \text{ kg}$ (BSQ) and $149.00 \pm 19.77 \text{ kg}$ (HBD). The 1RM normalized per kg of body mass was 1.54 ± 0.24 (BSQ) and 1.86 ± 0.29 (HBD). The average number of attempts during the progressive test was 8.3 loads (range: 7–10) for the BSQ and 8.5 attempts (range: 7–10) for the HBD exercise.

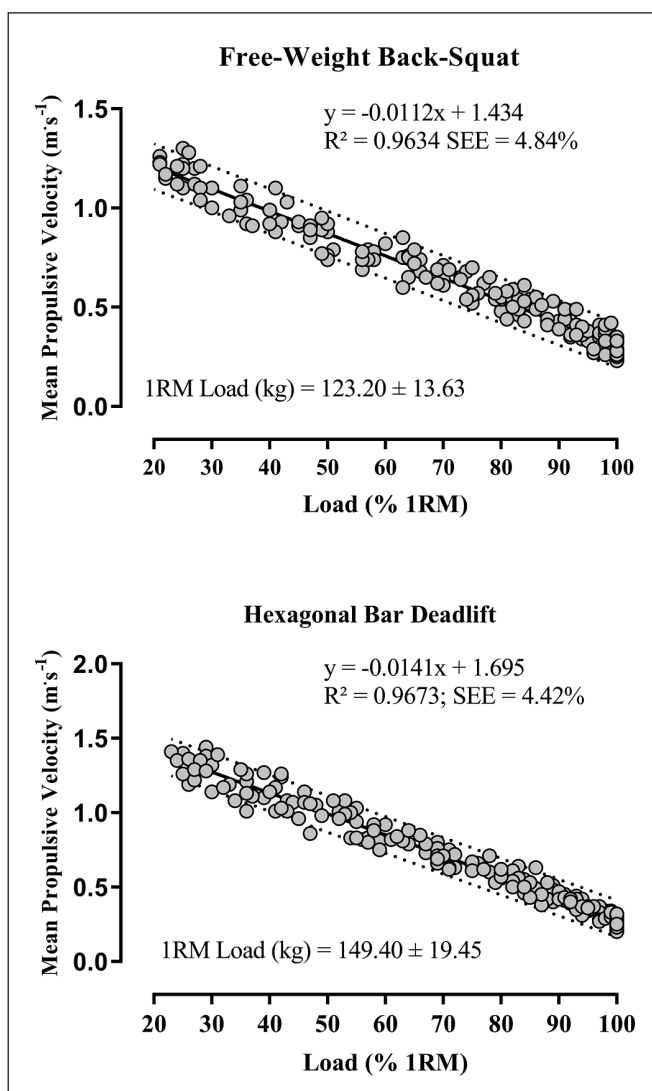


FIG. 1. General linear load-velocity relationship for free half back-squat and hexagonal bar deadlift exercises. Solid line shows the fitted curve to the data, and the dotted lines indicate the predicted 95% CI.

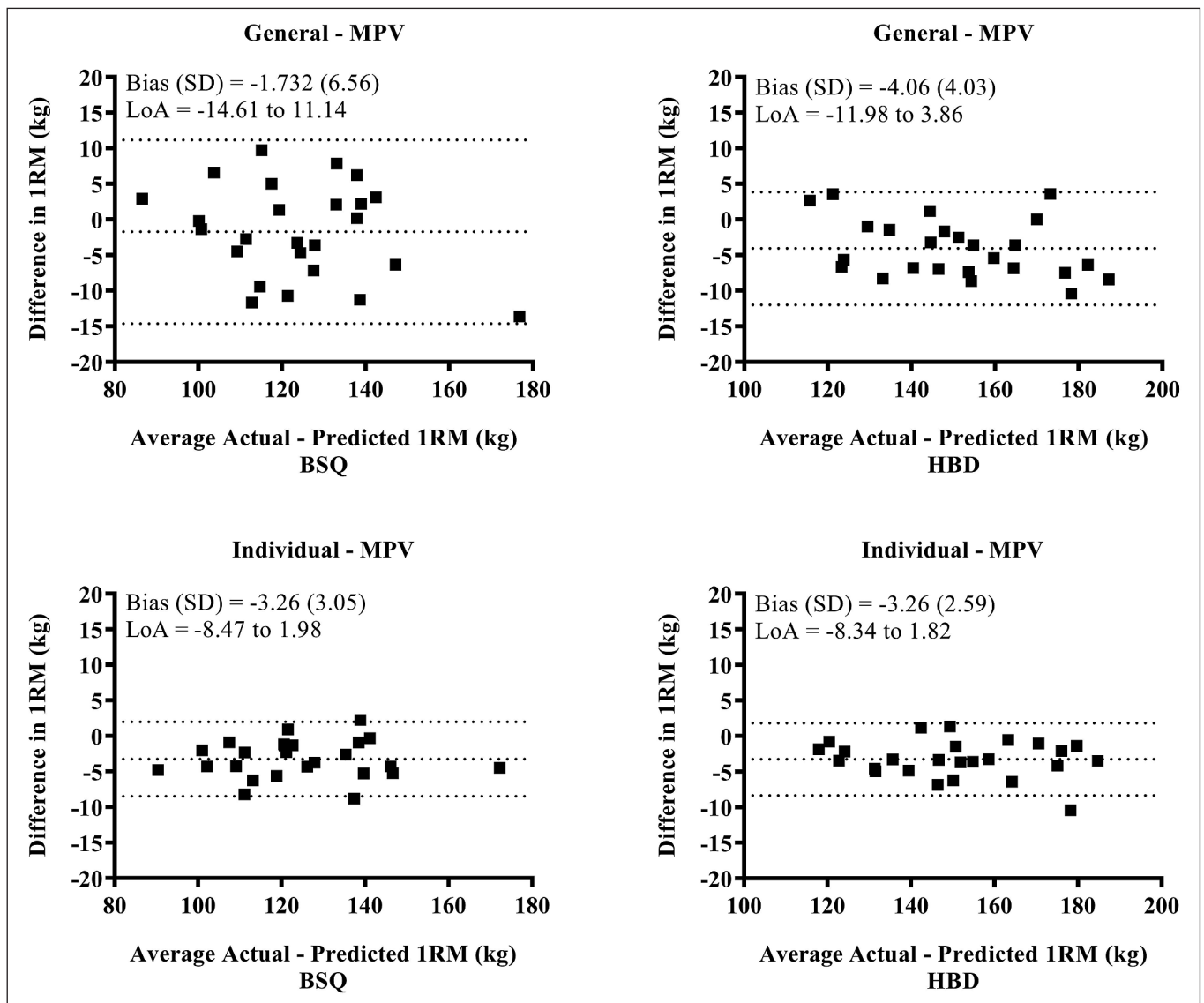


FIG. 2. Bland-Altman plots between actual and predicted 1RM load obtained from the general and individualized load-velocity relationship for the free half back-squat and hexagonal bar deadlift exercises. BSQ = back-squat exercise; HBD = hexagonal bar deadlift; SD = standard deviation; LoA = limits of agreement.

Load-velocity relationship

Figure 1 shows the results of the linear regression, plotting MPV against each %1RM for both the BSQ and HBD exercises for all data points (BSQ: $n = 210$; and HBD: $n = 211$). A very strong load-velocity relationship was found for the BSQ ($R^2 = 0.963$; $SEE = 4.84\%$) and HBD ($R^2 = 0.967$; $SEE = 4.42\%$) exercises. The individual load-velocity relationship provided better adjustments for the BSQ ($R^2 = 0.983 \pm 0.01$) and HBD ($R^2 = 0.989 \pm 0.01$) exercises than the general equation.

Bland-Altman plots showed high agreement between actual and predicted 1RM for both the BSQ (ICC = 0.968; 95% CI = 0.928 to 0.986) and HBD (ICC = 0.981; 95% CI = 0.831 to 0.994) exercises, using general equations (Figure 2). The individual load-velocity relationship showed higher agreement than the general equation

for both the BSQ (ICC = 0.987; 95% CI = 0.785 to 0.997) and HBD (ICC = 0.989; 95% CI = 0.810 to 0.997) exercises.

Predicting relative load (%1RM) from MPV data

The following equations were obtained from the linear regression to estimate %1RM for both exercises:

$$BSQ \text{ load } (\%1RM) = -85.638 \text{ MPV} + 125.43 \quad (R^2 = 0.963; \text{SEE} = 4.84\%)$$

$$HBD \text{ load } (\%1RM) = -68.648 \text{ MPV} + 118.79 \quad (R^2 = 0.967; \text{SEE} = 4.42\%)$$

The average MPV and the between-subjects %CV attained with each %1RM obtained from the general load-velocity relationship from 30% onwards up to 1RM, in 5% increments, are displayed in

TABLE 1. Mean propulsive velocity attained at which relative intensity (%1RM) in the free half back-squat and hexagonal bar deadlift exercises (Mean and standard deviation).

Load (%1RM)	Half Back-Squat			Hexagonal Bar Deadlift			P-Value
	MPV ($\text{m} \cdot \text{s}^{-1}$)	95% CI ($\text{m} \cdot \text{s}^{-1}$)	CV (%)	MPV ($\text{m} \cdot \text{s}^{-1}$)	95% CI ($\text{m} \cdot \text{s}^{-1}$)	CV (%)	
30	1.09 ± 0.07	1.06 to 1.12	6.60	1.29 ± 0.12	1.24 to 1.33	8.95	< 0.001
35	1.03 ± 0.07	1.00 to 1.06	6.54	1.21 ± 0.11	1.17 to 1.26	8.83	< 0.001
40	0.97 ± 0.06	0.95 to 1.00	6.47	1.14 ± 0.10	1.10 to 1.18	8.70	< 0.001
45	0.92 ± 0.06	0.90 to 0.94	6.40	1.07 ± 0.09	1.03 to 1.11	8.55	< 0.001
50	0.86 ± 0.05	0.84 to 0.89	6.33	1.00 ± 0.08	0.97 to 1.03	8.39	< 0.001
55	0.81 ± 0.05	0.79 to 0.83	6.26	0.93 ± 0.08	0.90 to 0.96	8.21	< 0.001
60	0.75 ± 0.05	0.73 to 0.77	6.20	0.86 ± 0.07	0.83 to 0.88	8.00	< 0.001
65	0.70 ± 0.04	0.68 to 0.71	6.15	0.78 ± 0.06	0.76 to 0.81	7.78	< 0.001
70	0.64 ± 0.04	0.62 to 0.66	6.11	0.71 ± 0.05	0.69 to 0.73	7.54	< 0.001
75	0.58 ± 0.04	0.57 to 0.60	6.12	0.64 ± 0.05	0.62 to 0.66	7.29	0.001
80	0.52 ± 0.03	0.52 to 0.54	6.19	0.57 ± 0.04	0.55 to 0.59	7.04	0.017
85	0.47 ± 0.03	0.46 to 0.48	6.37	0.50 ± 0.03	0.48 to 0.51	6.85	0.120
90	0.42 ± 0.03	0.40 to 0.43	6.73	0.43 ± 0.03	0.42 to 0.44	6.84	0.537
95	0.36 ± 0.03	0.35 to 0.37	7.40	0.36 ± 0.03	0.34 to 0.37	7.28	0.872
100	0.30 ± 0.03	0.29 to 0.31	8.57	0.29 ± 0.02	0.28 to 0.30	8.75	0.334

MPV = mean propulsive velocity; CI = confidence interval; CV = coefficient of variation.

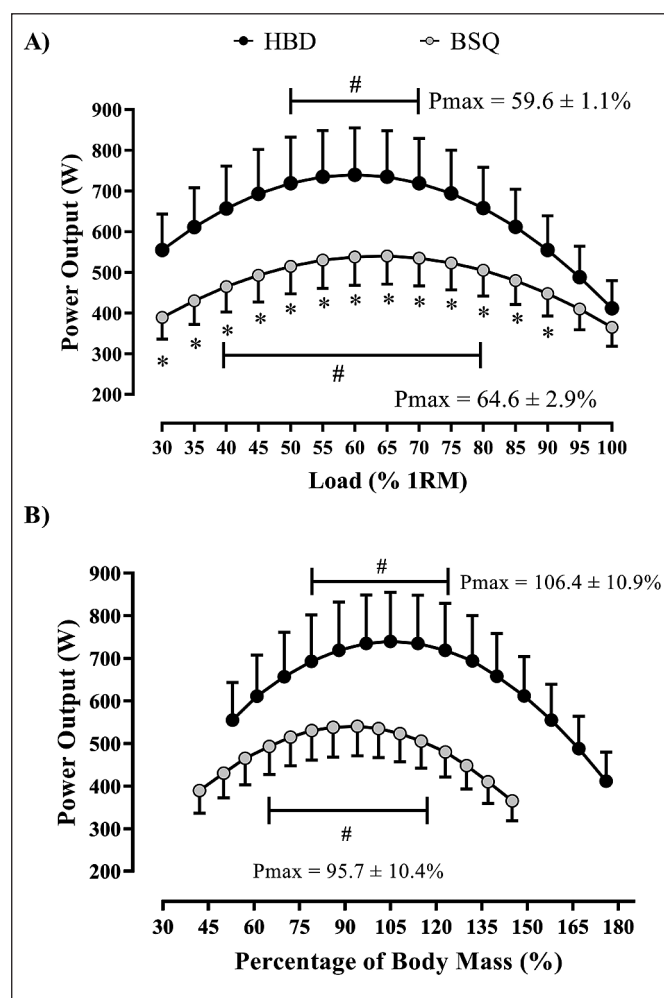


Table 1. MPV attained with loads below 80% 1RM was significantly higher for the HBD ($p < 0.05$) than the BSQ exercise.

Load-power relationships

The load which maximizes power output ($P_{\max}$) was $64.6 \pm 2.9\%$ ($CV = 4.56\%$) and $59.6 \pm 1.1\%$ ($CV = 1.83\%$) 1RM for the BSQ and HBD exercises, respectively (Figure 3). However, no significant differences were found for a range of %1RM for the BSQ (40–80% 1RM) and HBD (50–70% 1RM) exercises regarding $P_{\max}$ ($p > 0.05$). Higher power output was found for the HBD exercise than BSQ exercise (%1RM range: 30–90% 1RM; $p < 0.05$) (Figure 3a). Furthermore, the $P_{\max}$ relative to the percentage of body mass was $95.7 \pm 10.4\%$ ($CV = 10.86\%$) and $106.4 \pm 10.9\%$ ($CV = 10.25\%$) for BSQ and HBD, respectively. Nevertheless, no significant differences were found for a range of percentage of body mass for the BSQ (~65–123%) and HBD (~80–132%) exercises regarding $P_{\max}$ ($p > 0.05$) (Figure 3b).

FIG. 3. Load-power relationship for the free half back-squat and hexagonal bar deadlift exercises according to the %1RM (A) and percentage of body mass (B). HBD = hexagonal bar deadlift exercise; BSQ = back-squat exercise; open circle represents the $P_{\max}$ = load at which power output is maximized; # = the range of loads at which the power output is not significantly different than $P_{\max}$; * = Statistically significant difference between exercises at the same relative load; percentage of body mass = relative load from 30% onwards until 100% of 1RM, in 5% increments.

DISCUSSION

The main findings of the present study were as follows: (a) the load-velocity relationships in both the BSQ and HBD exercises were highly linear, which enables accurate load prescription from movement velocity; (b) HBD elicited higher kinematic outputs in a range of %1RM ($< 90\%$ 1RM) compared to BSQ exercise; (c) the loads that maximize the power output were $\sim 66\%$ for the BSQ and $\sim 60\%$ 1RM for the HBD. However, no power output differences were found in a wide range of %1RM related to the $P_{\max}$ for the BSQ (40–80% 1RM) and HBD (50–70% 1RM) exercises.

The very strong load-velocity relationships for both BSQ and HBD exercises ($R^2 > 0.96$; $SEE < 5\%$ 1RM) enable strength and conditioning coaches to determine with great precision the 1RM from the MPV during a single repetition performed at maximum effort using submaximal loads on a daily basis. This statement is reinforced by the low %CV found for the MPV attained at each %1RM ($< 10\%$) and the high agreement between actual and predicted 1RM ($ICC > 0.96$) in both exercises. The MPV difference between each 5% increment in %1RM was $\sim 0.06 \text{ m} \cdot \text{s}^{-1}$ (BSQ) and $\sim 0.07 \text{ m} \cdot \text{s}^{-1}$ (HBD). From a practical perspective, this means that changes in movement velocity of $\pm 0.06 \text{ m} \cdot \text{s}^{-1}$ (BSQ) and $\pm 0.07 \text{ m} \cdot \text{s}^{-1}$ (HBD) might represent a need to adjust the training load ($\pm 5\%$ 1RM).

The strong load-velocity relationship in the BSQ performed on the Smith machine [6, 10, 15] and the traditional deadlift [8, 16, 17, 31] has already been described, and the current study has extended that understanding to their variants (i.e., free-mode BSQ and HBD). Performing the BSQ using the Smith machine equipment limits the horizontal displacement of the bar in lifting, which might enhance the model prediction [13]. Nevertheless, our data showed that the velocity-based approach can also be used to estimate 1RM in the free-mode BSQ ($R^2 = 0.96$). Likewise, to our knowledge, this is the first study to show that the bar velocity can estimate the 1RM in the HBD variant ($R^2 = 0.96$). Given that the free-mode BSQ and HBD exercises are widely used in RT programmes to increase lower-body strength [9, 32], our results have important practical application by providing general equations to assist strength and conditioning coaches to incorporate the VBT paradigm in these exercises.

The individual load-velocity relationship showed a slightly better (but not relevant) adjustment of the load-velocity relationship ($R^2 > 0.98$ versus $R^2 > 0.96$, for the general equation). This is not surprising since the general equations do not consider some individuals' characteristics that might affect the kinematic outputs in lifting (i.e., age, height, and limb lengths) [33, 34]. However, in practical terms, it is important to consider how meaningful these slight differences between general and individual load-velocity relationships are regarding training prescription or loading adjustment. For example, previous studies have already demonstrated the efficiency of the group-based equations to induce muscular strength and power adaptations [35, 36]. In a practical setting, strength and conditioning coaches seek to implement valid methods for prescribing the exercise load, but also simple and easy approaches to determine

how their practitioners are responding to training. Hence, we suggest that the general equations provided here can be safely used to prescribe and adjust exercise load as a user-friendly and time-saving approach.

Supporting our second hypothesis, the relationship between %1RM and movement velocity was exercise-dependent ($\leq 80\%$ 1RM; $p < 0.05$). HBD exercise elicited higher mechanical power in a range of loads when compared to the BSQ exercise (30–90% 1RM; $p < 0.05$). Therefore, the applied force against light-moderate loads was greater during the HBD, since the lighter the %1RM was, the greater was the MPV difference between the two exercises. The difference in bar velocity found in our study might be explained by the advantageous lifting position of the external load when the HBD exercise is performed (i.e., upright torso position, reduced horizontal displacement of the bar, and less resistive torque) compared to the bar positioned on the shoulder (i.e., BSQ exercise) [18, 20, 21]. Therefore, it seems that the HBD can be prescribed to alter the movement pattern, muscular requirements, and kinematic outputs during RT programmes. Future studies are warranted to investigate how this kinematic advantage might translate into additional training adaptations.

Despite the clear difference in mechanical power between exercises, we observed that the loads related to $P_{\max}$ occurred at quite similar %1RM for both the BSQ ($\sim 65\%$ 1RM; $MPV = \sim 0.70 \text{ m} \cdot \text{s}^{-1}$) and HBD ($\sim 60\%$ 1RM; $MPV = \sim 0.86 \text{ m} \cdot \text{s}^{-1}$) exercises. However, loads in the range 40–80% (BSQ) and 50–70% 1RM (HBD) did not differ statistically concerning $P_{\max}$ (Figure 3). These data strongly support previous studies showing that mechanical power output is quite similar across a range of light-moderate loads in other resistance exercises such as the bench press (20–60% 1RM) [37], bench pull (20–70% 1RM) [37], traditional deadlift (40–80% 1RM) [17], and half-BSQ (25–85% 1RM) [10]. These findings raise some questions about how much attention has been given to determining a single “optimal load” [24, 37, 38]. This is supported by previous studies showing improvements in strength-power ability using a wide range of moderate (i.e. 55–70% 1RM) [39] to heavy loads (i.e. 70–85% 1RM) [40]. From a practical perspective, these data can be used for prescribing exercise load based on the individuals' training goals (i.e., velocity- or force-biased).

Although there is a growing number of devices available to assess kinematics in resistance exercise, they may be not accessible to many RT practitioners. When such devices are unavailable, a possible alternative is prescribing exercise load based on the percentage of body mass [38]. When plotting the mechanical power output by individuals' body mass percentage, our results showed that the body mass percentage which maximizes mechanical power was $95.7 \pm 10.4\%$ ($CV = 10.86\%$) and $106.4 \pm 10.9\%$ ($CV = 10.25\%$) for the BSQ and HBD exercises, respectively. Despite the moderate between-subjects' variability of this approach, no statistically significant differences were found in power output across a wide range of percentage of body mass for both the BSQ (~ 65 –123% of body mass) and

HBD (~80–132% of body mass) exercises. Thus, although a more objective assessment is necessary, this approach might be a much more feasible and practical alternative for strength and conditioning coaches to prescribe exercise load when such devices are not available [38].

Despite the novelty of our findings, some study limitations are worth mentioning. Our participants were resistance-trained (population who can lift ~1.5 [BSQ] and ~1.8 [HBD] their body mass), which limits the extrapolation of our results to individuals with higher RT backgrounds (i.e., highly trained athletes). Furthermore, we only recruited men, and future studies should investigate the load-velocity and load-power relationships for women; thus, cross-validation of our equations to other populations is required. We only used a linear position encoder to measure bar kinematics, and it would be relevant to use a motion analysis system and muscle activation to provide further understanding of the mechanical pattern and muscle activation in lifting between the exercises performed here.

From a practical perspective, the use of the load-velocity relationships provided here might be useful for strength and conditioning coaches to monitor and prescribe the exercise load of their practitioners in real time on an individual daily basis. For example, a target MPV might be chosen beforehand during the warm-up, depending on the specific training goal being pursued. Furthermore, the range of light-moderate loads that elicited similar power output to P_{max} raises some questions about the effectiveness of determining a single “optimal load”. Collectively, these data might assist strength and conditioning coaches to implement movement velocity as a feasible approach

to determine exercise loads. Finally, if devices such as linear encoders are not available, the percentage of body mass could be used as a practical alternative for prescribing exercise load, despite moderate inter-subject variability.

CONCLUSIONS

In summary, we found that the general load-velocity relationship was highly linear in both the BSQ and HBD exercises, which enables the accurate estimation of the 1RM from MPV recorded during a single repetition performed at maximum effort. In addition, HBD elicited higher mechanical outputs than BSQ, but the range of submaximal loads capable of maximizing power output in both exercises occurred at a quite similar %1RM. Therefore, strength and conditioning coaches can use the load-velocity and load-power relationships provided here as a quick and easy approach to prescribe and adjust the exercise load during RT programmes on a daily basis.

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Conflict of Interest

The authors declare no conflict of interest.

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Acute effects of different external compression with blood flow restriction on force-velocity profile during squat and bench press exercises

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ABSTRACT: The aim was to compare the acute effects of bench press (BP) and squat (SQ) exercises with blood flow restriction (BFR) (40%, 60%, 80% and 100% of the complete arterial occlusion pressure (AOP)) and without BFR (CON) on the mean propulsive (Vel_{MED}) and maximum (Vel_{MAX}) bar velocity. Fourteen healthy, physically active males (age, 23.6 ± 4.1 years; height, 1.85 ± 0.11 m; body weight 85.4 ± 4.1 kg) took part in the study. There was one set for each testing condition (CON, 40%, 60%, 80% and 100%) with 6 repetitions for BP and 6 repetitions for SQ, at 60% of 1RM, and 3 minutes of recovery between sets. The results showed statistically significant differences of the sets with 80% BFR vs. CON (mean difference [MD] = $0.035 \text{ m} \cdot \text{s}^{-1}$, $p < 0.05$, ES = $0.52 [1.02-0.03]$) and 100% BFR sets vs. CON (MD = 0.074 , $p < 0.001$, ES = $1.08 [1.79-0.38]$) for BP. In the SQ exercise, statistically significant differences were found between 100% BFR vs. CON (MD = $0.031 \text{ m} \cdot \text{s}^{-1}$, $p < 0.05$), vs. 100% BFR 40% (MD = $0.04 \text{ m} \cdot \text{s}^{-1}$, $p < 0.05$). Trend analysis showed a statistically significant linear trend ($F_{[1,9]} = 34.9$, $p < 0.001$, $F_{[1,13]} = 27.32$, $p < 0.001$) for the Vel_{MED} in relation to the different levels of BFR. In conclusion, our results showed that BFR levels above $\sim 80\%$ AOP (BP) and $\sim 100\%$ AOP (SQ) produce a Vel_{MED} improvement at 60% 1RM.

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INTRODUCTION

Resistance training (RT) is a useful tool for increasing athletic performance as well as improving health [1, 2]. Traditionally, to improve muscle mass and strength capacity, a range of intensities within 60–85% of one-repetition maximum (1RM) has been recommended [3]. However, this methodology has shown remarkable evolution in recent years. New training methods and technologies such as electrostimulation [4], isoinertial methods [5] mechanical vibrations [6, 7], blood flow restriction (BFR) [8], and different combinations [9] have been a recent subject of research in the specific research literature [10].

The interest in BFR training has increased during the last five years. This kind of training methodology can provide an effective alternative to conventional training [11]. This methodology requires the application of a cuff on the proximal part of the limb [12]. The cuff should generate an external occlusion leading to BFR, which is the basis of this methodology. Therefore, of all variables that configure the BFR, the level of occlusion must be properly controlled. In this regard, the arterial occlusion pressure (AOP) has been suggested as the most precise way to prescribe the level of pressure in BFR [13]. Several

pieces of research have shown that the use of AOP can be combined with RT stimuli to cause gains in strength and hypertrophy [14]. The AOP-based RT training methodology (AOP-RT) has become popular in recent years due to its potential to improve strength [11] and muscle hypertrophy [12] by applying light loads ($\sim 20-40\%$ of 1RM). The key point of this type of methodology is that the results obtained show similar gains compared to traditional training with medium/high loads of 60–85% 1RM [11]. This feature offers interesting practical applications in cases where RT with high loads is contraindicated (i.e., older people, patients with chronic diseases, or in recovery processes for musculoskeletal pathologies) [15].

Although the application of this BFR-RT methodology within athletic performance could yield performance benefits in many disciplines [16, 17], the latest trends in RT include the advice not to work in ranges close to full fatigue [18]. In this regard, this stresses the importance of implementing velocity as a key variable for measuring the intensity during training [19, 20]. RT training for improving sports performance is closely related to the velocity at which the load has been performed [21]. The velocity has traditionally been

analysed globally although, for greater precision, it should be broken down into 3 areas: 1) mean velocity, 2) mean propulsive velocity (Vel_{MED}), and 3) maximum velocity (Vel_{MAX}) [22]. The magnitude of mean propulsive velocity (Vel_{MED}) determines objectively the functional capacity of a subject [23], their performance level, and even their level of fatigue [24]. In addition, it contributes to optimization of the instantaneous load and avoidance of overtraining [23]. In this sense, it seems appropriate to train with multi-joint exercises for the RT [25] without neglecting the production of Vel_{MED} in addition to providing large increases in power, with a high degree of transfer to sports movements [26].

The muscle performance is determined by its contractile capacity and neuromuscular activation [27]. In BFR training, it has been shown to acutely affect muscle activation and neuromuscular fatigue [28]. These changes produce mechanical muscle tension that increases the force of muscle contractions [29]. This variation in muscle tissue produces an increase in metabolic stress and the sensitivity of the intracellular anabolic and catabolic pathways [30]. The increased sensitivity leads to the faster synthesis of muscle proteins [29]. Recently, Wilk *et al.* [31] studied the acute effects of external compression with BFR at 100% and 150% of AOP on maximal strength and strength-endurance performance during bench press exercise (BP) in healthy strength-trained men. Results obtained from this study revealed an increase of maximal strength with high external compression (i.e., 150% vs. without BFR, effect size [ES] = 0.19). The number of repetitions and time under tension were also increased significantly when subjects were tested at 150% of BFR. For this reason, the authors concluded that maximal strength as well as endurance performance was increased when high external compression was applied. In this line, Wilk *et al.* [32] found that type of cuffs (i.e., wide

96 × 13 cm vs. narrow 57 × 9 cm) during BFR had an acute effect on bar velocity and power output during BP exercise at 70% 1RM and using 90% of arterial occlusion. The authors found an increased in peak bar velocity (i.e., 18%, ES = 1.65), mean bar velocity (i.e., 13%, ES = 1.00) and peak power output (i.e., 15%, ES = 1.07) when wide BFR was compared to narrow BFR, and without BFR [33, 34]. Therefore, type of cuffs used during BFR had an influence on velocity and power in BP exercise. The authors speculate on the possibility of a “rebound effect” that would explain the increase in the peak velocity, not the average. This effect is attributed to the mechanical energy generated by the cuff, and therefore the width of the cuff would be an influential factor [34].

A recent study performed by Wilk *et al.* [32] showed an acute effect of type of cuffs on bar velocity in BP exercise, but no studies have investigated the acute effect of different pressure levels on bar velocity in BP and squat (SQ) exercises. Therefore, the main objective of this study was to analyse the acute effect of different degrees of partial occlusion in the arms and legs (without occlusion, 40%, 60%, 80% and 100% of AOP) on bar velocity (i.e., mean velocity of propulsive phase [Vel_{MED}]) in bench press and squat exercises at 60% of 1RM in healthy active subjects.

MATERIALS AND METHODS

Participants

A total of 14 males took part in this study. All participants were healthy and physically active. The mean and standard deviation ($\pm$ SD) of age, height, and body mass were 23.6 ± 4.1 years, 1.85 ± 0.11 m, and 85.4 ± 4.1 kg, respectively. The 1RM values were 79.33 ± 14.53 kg and 76.11 ± 6.95 kg, with a relative strength index [35] of 1.07 ± 0.003 and 1.12 ± 0.04 for BP and

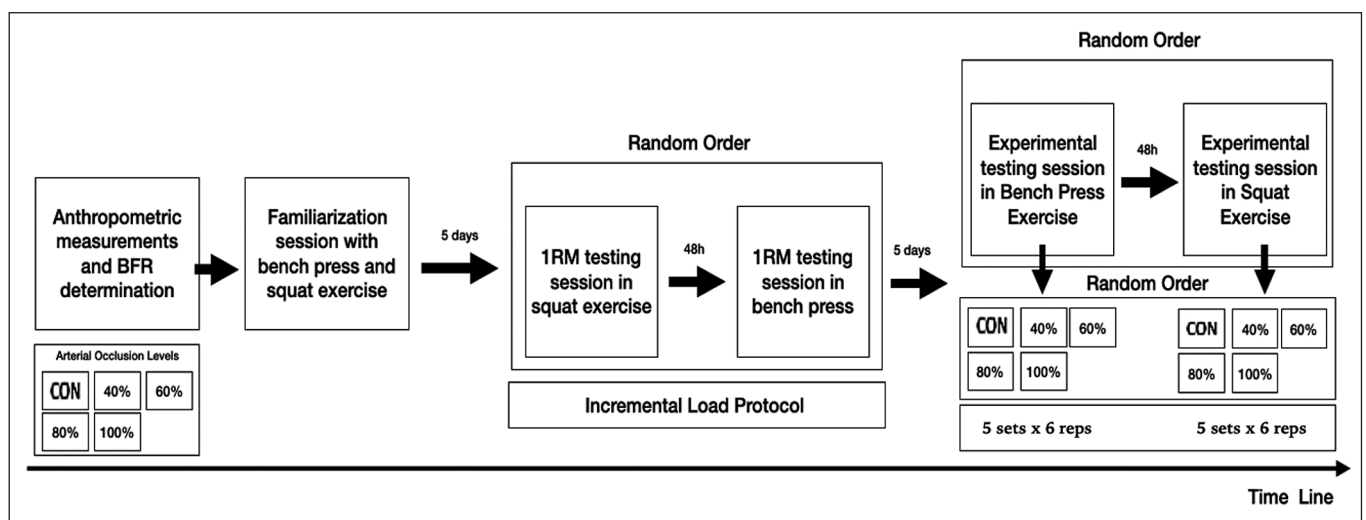


FIG. 1. Graphic representation of the experimental design.

BFR: blood flow restriction. CON: without blood flow restriction. 1RM: 1 repetition maximum.

SQ exercises respectively. All study participants reported previous recreational experience in external resistance training for 1 to 3 years. Prior to conducting the experiment, all participants received an explanation of the purpose of the study, the evaluation procedures, and the potential risks of participating in it. Once informed, all participants signed informed consent. The experimental procedure of this investigation complied with the ethical principles of the Declaration of Helsinki. This study was approved by the University Ethics Committee (UA / 2018–11–15).

Experimental setting

All subjects were recruited for a total of 6 visits to the laboratory. The intervention protocol is described in Figure 1. During the first visit, informed consent was signed, and subsequently, anthropometric measurements corresponding to body mass (Avery Ltd Model 3396 ABV) and height (Holtain Ltd., Dyfed, Wales) were made. In addition, the level of partial occlusion of the venous return was individually determined for the upper and lower body. On the second visit, the participants performed a familiarization session with BP and SQ exercises. The familiarization session consisted of standardized warm-up (i.e., 10 minutes of continuous running) arm and hip mobility exercises.

Determination of arterial occlusion pressure (AOP)

For AOP measurement, an ultrasound machine with an echo-Doppler probe was used (Doppler Sonosite Titan ultrasound machine, Sonosite, Inc., Bothwell, WA). The determination procedure took place a week before the testing procedures and was carried out by recording the flow wave next to the electrocardiographic vascular pulse scan, taking images of flow waves at the level of the inguinal and brachial artery fold [36]. Participants remained in a prone position on a stretcher during the entire procedure [37]. The pneumatic cuff (Komprimeter standard pneumatic Rudolf Riester GmbH – Bruckstr. Jungingen Germany) used for intervention was placed on the proximal portion of the arm (57 × 9 cm) and leg (96 × 13 cm) to determine 100% arterial occlusion pressure using a Doppler ultrasound scan of the femoral and brachial artery. External pressure was increasing and monitored with a manometer until the signal of blood flow disappeared in the echo-Doppler, and recorded as 100% AOP in mmHg [38]. From this value, established as 100% AOP, the relative percentages of AOP (80%, 60%, 40%) were calculated and subsequently used in the experimental protocols. Table I shows descriptive data of these relative percentage values of AOP in participants.

Familiarization session and 1RM test

Five days prior to the beginning of the testing procedures, participants performed a preliminary familiarization session with SQ and BP with a Smith machine (Multipower Fitness Line, Peroga, Spain), which allows a constant vertical movement of the bar throughout the execution and prevents lateral movement of the bar. Two certified specialists (Certified Strength and Conditioning Specialist (NSCA-CSCS)) monitored

the performance of the correct technique of both exercises. The BP exercise began in the supine position on a flat bench, with the feet resting on the floor and the hands resting on the bar slightly wider than the distance between the shoulders [39]. Bench positions and grip widths were measured to be reproduced individually for each lift. The course of the bar had to go down to the chest, just above the nipples at a controlled velocity and wait there for approximately 1 s, until the order to start the concentric phase was given. This momentary pause between the eccentric and concentric phases was applied to minimize the influence of the rebound effect and allow more consistent measurements [40]. Bouncing the bar on the chest or lifting the shoulders or torso off the bench was not allowed. In the SQ exercise the subjects started with their knees and hips fully extended forming an upright position with feet apart at shoulder height and the bar resting on the back at the level of the acromion [41]. Subjects lowered the bar until their upper thighs were below horizontal (parallel with floor) [42]. Then the reverse movement was started and the initial vertical position was ascended. In both exercises (BP and SQ) the eccentric phase was controlled and constant, but the concentric phase was carried out at maximum velocity. The execution of these exercises was always monitored by 2 experienced evaluators (NSCA-CSCS).

This familiarization session began with a warm-up, consisting of 5-minute running on a treadmill at 10 km/h and 5 min of lower limb mobilization exercises for a SQ day. After that, participants performed two sets of 8 and 6 repetitions of SQ with three minutes of rest between sets and loads of 20 and 30 kg, respectively [43]. After 48 hours, for familiarization with the BP exercise, it began with 5 min of exercise bike cycling at a light self-perceived intensity, followed by 5 min of passive stretching and mobility exercises for the upper body, for two sets of 5 repetitions with loads of 20 and 40 kg [44].

1 repetition maximum in squat and bench press exercises

After the standardized dynamic warm-up, an indirect and incremental test was performed to obtain the 1RM without exceeding 80% of the estimated 1RM. The 1RM allows one to know the individual load at 60% 1RM in the full squat and wide grip bench press exercise [45, 46]. The initial load was established at 20 kg (bar weight) and was progressively increased by 10 kg loads until the mean propulsive velocity (Vel_{MED}) obtained was $< 0.8 \text{ m} \cdot \text{s}^{-1}$. Then, the load was adjusted individually, with small increments (from 2.5 to 5 kg) to accurately determine 1RM at the maximum concentric velocity, with an eccentric phase that was performed at a controlled average velocity ($\sim 0.57\text{--}0.77 \text{ m} \cdot \text{s}^{-1}$). Three repetitions were performed for light loads ($\leq 50\%$ 1RM; $Vel_{MED} \geq 0.98 \text{ m} \cdot \text{s}^{-1}$), two for medium loads (50–80% 1RM; $Vel_{MED} \sim 0.90\text{--}0.68 \text{ m} \cdot \text{s}^{-1}$), and only one repetition for the heaviest loads ($> 80\%$ 1RM; $Vel_{MED} \leq 0.68 \text{ m} \cdot \text{s}^{-1}$). The rest between sets ranged from 3 minutes ($< 80\%$ 1RM) to 5 minutes ($> 80\%$ 1RM), performing a complete neuromuscular recovery and receiving verbal stimuli to reach maximum velocity. The assessment device used was a linear encoder (Chronojump, Barcelona, Spain), with a sampling rate of 1.000 Hz.

Procedures (experimental testing session)

The testing procedures were summarized in Figure 1. All experimental sessions started with a standardized warm-up identical to that used in the familiarization session. Then, each participant performed 5 sets in a randomized order, with each BFR% established (100%, 80%, 60%, 40%, and 0% –CON–) for 6 repetitions in BP and 6 repetitions in SQ exercise (48 hours after). The load was calculated at 60% of 1RM by polynomial equation [47]. For each set, a load of %1RM was used, since it is the percentage that achieves the best record in the tests, based on previous research [48–50]. This load was individually adapted through second-order polynomial [47] settings to the velocity and progressive load data during warm-up without BFR [24]. During the performance of the different sets with specific %AOP, participants were encouraged to perform each concentric repetition as quickly as they could, whereas the eccentric phase [40, 44] was performed at the controlled average velocity of $< 0.80 \text{ m} \cdot \text{s}^{-1}$. There were 3 minutes of rest between sets, during which the BFR was not maintained. Pressure levels of each %AOP were controlled during BFR experimental intervention in each set. The test procedures were performed at the same time of day for each participant, and under the same conditions (20 °C - 22 °C and 55% - 65% humidity).

Statistical analysis

All variables were expressed as mean and SD. Furthermore, all the dependent variables fulfilled the assumption of normality (i.e., Shapiro-Wilk test, $p > 0.05$). To analyse the influence of degrees of occlusion on execution velocity, an analysis of variance of repeated measures (RM ANOVA [5]) was performed. The degrees of occlusion had a total of 5 levels (i.e., CON, 40%, 60%, 80%, and 100%). When the sphericity assumption was not fulfilled, the degrees of freedom were corrected using the Greenhouse–Geisser approximation. The Bonferroni post hoc test was performed to analyse comparisons for each of the levels. This analysis was performed for BP and SQ exercises. The effect size (ES) was expressed using Cohen's *d*. The level of significance was established at $p < 0.05$. All analyses were

performed using statistical analysis software (SPSS Inc, Chicago, Illinois, USA).

RESULTS

The 1RM value for BP and SQ corresponded to $79.33 \pm 14.53 \text{ kg}$ and $76.11 \pm 6.95 \text{ kg}$, respectively. The 60% 1RM load corresponded to $47.6 \pm 8.7 \text{ kg}$, for the bench press exercise and $45.67 \pm 4.17 \text{ kg}$, for the squat exercise. Table I shows the descriptive statistics of the mean propulsive velocity (Vel_{MED}) ($\text{m} \cdot \text{s}^{-1}$), and the amount of occlusion (mmHg) for all the levels of occlusion.

In relation to BP exercise, RM ANOVA showed statistically significant differences ($F_{[4,36]} = 7.15$, $p < 0.001$, $h^2_p = 0.44$) in main effect levels of the occlusion variable. Bonferroni's post hoc test showed statistically significant differences in the comparison of 80% BFR vs. CON (mean difference [MD] = $0.035 \text{ m} \cdot \text{s}^{-1}$, $p < 0.05$, ES = $0.52 [1.02-0.03]$) and 100% BFR vs. CON (MD = $0.074 \text{ m} \cdot \text{s}^{-1}$, $p < 0.001$, ES = $1.08 [1.79-0.38]$), see Figure 2A.

In SQ exercise, the RM ANOVA showed statistically significant differences ($F_{[2.59, 33.66]} = 6.26$, $p < 0.003$, $h^2_p = 0.33$) in the main effect of the variable levels of occlusion. Bonferroni's post hoc test showed statistically significant differences in the set comparison 100% AOP vs. CON (MD = $0.031 \text{ m} \cdot \text{s}^{-1}$, $p < 0.05$), 100% AOP vs. 40% AOP (MD = $0.04 \text{ m} \cdot \text{s}^{-1}$, $p < 0.05$), see Figure 2B.

Moreover, the trend analysis showed a statistically significant linear trend ($F_{[1,9]} = 34.9$, $p < 0.001$, $F_{[1,13]} = 27.32$, $p < 0.001$) for the execution velocity in relation to the different levels of occlusion (CON, 40%, 60%, 80% and 100%), for the BP and SQ exercises, respectively. Finally, the percentage difference in the Vel_{MED} between the level without occlusion, and the different percentages with occlusion, were 4.57%, 4.74%, 4.78% and 10.02% for 40%, 60%, 80% and 100% of AOP, respectively.

DISCUSSION

The main objective of this study was to analyse the acute effects of BFR at different degrees of occlusion pressure levels (i.e., CON, 40%, 60%, 80%, and 100% AOP) on the BP and SQ exercises at 60%

TABLE 1. Descriptive statistics of the main variables of this study. Execution velocity ($\text{m} \cdot \text{s}^{-1} \pm \text{SD}$) and the amount of occlusion (mmHg $\pm \text{SD}$) of the AOP.

		CON	LEVEL OF COMPRESSION FROM AOP			
			40%	60%	80%	100%
Bench Press Exercise	Vel_{MED}	0.73 ± 0.06	0.77 ± 0.06	0.77 ± 0.07	0.77 ± 0.07	0.81 ± 0.05
	COMPRESSION	0	62.2 ± 6.1	93.3 ± 9.1	124.4 ± 12.1	155.5 ± 15.2
Squat Exercise	Vel_{MED}	1.02 ± 0.08	1.01 ± 0.09	1.05 ± 0.08	1.04 ± 0.07	1.05 ± 0.08
	COMPRESSION	0	68.3 ± 7.7	102.4 ± 11.6	136.6 ± 15.5	170.7 ± 19.4

CON: without blood flow restriction. AOP: arterial occlusion pressure. Vel_{MED} ($\text{m} \cdot \text{s}^{-1}$): mean propulsive velocity in meters by seconds. mmHg: millimetres of mercury.

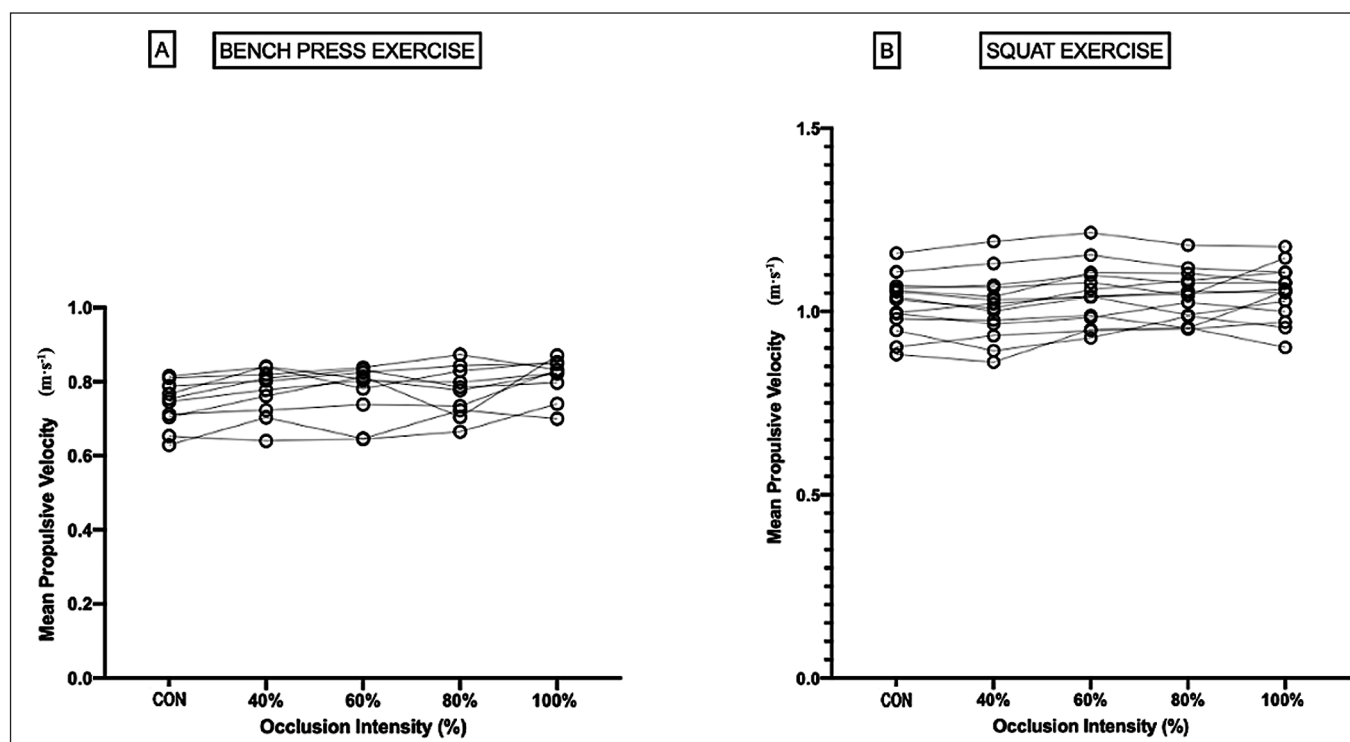


FIG. 2. Graphical representation of the mean propulsive velocity, in relation to the levels of partial occlusion of the venous return, at 60% of the 1 maximum repetition (1RM) for the bench press (A) and squat (B) exercise.

1RM in healthy and active men. One of the key findings was that the mean velocity of the propulsive phase at 60% 1RM was higher from 80% occlusion in comparison to CON in BP exercise and 100% occlusion in comparison to CON in SQ. In addition, the trend analysis concerning the level of occlusion described a positive linear trend, a higher level of occlusion, and a higher velocity of execution, for BP and SQ exercises.

According to our results, the level of occlusion had an acute effect on the execution velocity in BP and SQ exercises, greater effects the higher the level of occlusion. General recommendations regarding the use of BFR to improve strength and hypertrophy indicate that between 40 and 80% of AOP should be applied. Therefore, if these adaptations are the primary focus of our training, one should prioritize training based on execution velocity. However, there are few general recommendations [29] on how to work using the BFR approach to achieve these goals. Currently, there are recent scientific studies that have studied the effects that RT-BFR can have on the velocity of execution in training with external resistance [31, 32, 33, 53].

Recently, the acute effects of the application of different levels of occlusion (i.e., WO, 100 vs 150% AOP) on multiple variables (i.e., 1RM, time under tension, number of repetitions before a load) in BP exercise were assessed [31]. This study showed that compared to the no-occlusion condition, for the 1RM assessed, the number of total repetitions at 60% 1RM and the time under tension

were greater when applying a BFR of 150% AOP [31]. Moreover, the velocity of execution evaluation, (i.e., mean and peak) did not show variations throughout the different experimental conditions [31]. Wilk et al. [31] observed an acute increase in performance and suggested the possibility of a correlation between the level of external occlusion and the acute potentiation response for BP. In contrast, we found a significant positive relationship between the increase in the level of occlusion and the Vel_{MED} (see Table 1). These differences could be due to our study not having measured the 1 RM in each occlusion condition and not including reaching muscle failure. Training to muscle failure could cause a progressive loss of velocity, which increases exponentially with the number of repetitions performed [51]. In muscle failure exercises, the Vel_{MED} and Vel_{MAX} register decrease, and could occur prematurely under BFR conditions [52].

In another study, Wilk et al. [32] found large improvements in Vel_{MED} and Vel_{MAX} after BFR-RT with wide cuff (10 cm) intervention on BP. Larger increases in Vel_{MED} compared to the present study could be due to differences in the load percentage (70% vs. 60%), relative strength of the participants (1.2 vs 1), number of repetitions (3 vs. 6), and/or small differences in cuff size (10 vs. 9 cm). In contrast, in another study by Wilk et al. [33] which applied a gradual increase from 20 to 90% 1RM with 10% increments, no significant improvements in Vel_{MED} were obtained (in 60% RM) on BP. These results, contrary to the previous ones, could be due to the difference

in cuff size (narrow, 4 in [33], 9 in present study and 10 cm in [32]). Regarding SQ exercise, Wilk *et al.* [53] found, in an incremental study from 40 to 90% 1RM, with increases of 10% of 1RM, no significant differences in Vel_{MED} at ~80% AOP. In the present study, significant increases in Vel_{MED} were found, but at higher occlusion levels than in the Wilk *et al.* [53] (~100% vs. ~80% AOP) study. Perhaps higher levels of occlusion may be needed to influence Vel_{MED} in the lower extremities.

It has been established that the BFR causes physiological changes in the metabolic stress [53] that could be related to improvements in Vel_{MAX} and Vel_{MED} , as a consequence of an increase in lactate concentrations and acidity (↓ pH) in the intramuscular environment [54]. Furthermore, the BFR causes increased sympathetic activity and nerve impulse transmission [55] which enhances the activation of motor units, recruiting predominantly FT motor units (Fast twitch fibres) [56]. The conclusions proposed by Loenneke *et al.* [55] suggest that the neuromuscular effects with BFR application could have positive effects on the production of force and velocity. Another possible explanation for the positive effects of RT-BFR on Vel_{MAX} and Vel_{MED} could be related to mechanical factors associated with the width of the cuff. These advantages could be due to the mechanical work generated by the compression of the cuff and the loss of performance caused by the onset of fatigue [57]. Recent research suggests that the mechanical advantage of the compression of the cuff could increase with the application of high pressures [58]. The compression and associated effects could increase the efficiency of the mechanical joint [30] as a consequence of increased joint stability [59] and therefore allow more force to be developed [31]. The increase in the force that causes this compression is produced by an accumulation of energy in the eccentric phase that is produced in the concentric phase [34, 58, 60].

The BFR application methodology to improve sports performance has focused on guidelines for improving strength and hypertrophy [54]. Recently, it has been proven the effects of the use of BFR applied in specific movements of sports, aiming at the effects of greater specificity and transfer [61, 62, 63]. However, when aiming to train velocity-based RT-BFR it seems that it would be better to

train at a load of 60–70% RM with a wide cuff and at occlusion levels above ~80% AOP for the BP and close to ~100% AOP for SQ. Another possible aspect to consider is that the influence of BFR on muscle activity could be modified by the characteristics of exercise [34]. For instance, differences between BP and SQ exercise could be produced by applying the cuff (BFR) on the main or another primary muscles [64]. In the BP the cuff is applied directly on the triceps brachii muscle, having less effect on the primary pectoral muscles and anterior deltoid [65]. The type of exercise performed could influence the strength and power variables in BFR conditions [65]. In addition, in the SQ exercise, the application of BFR in the lower extremities also has an effect on the main muscles [34].

Despite these findings, limitations from the current research are worthy of consideration. Only 60% of the load was analysed in relation to the force-velocity profile of each participant, and the relative strength of the participants was not established as an inclusion criterion. Future studies should analyse the influence of different occlusion conditions on ranges of upper and lower loads (*i.e.*, > 80% 1RM and < 40% 1RM) and chronic effects of BFR on the force-velocity profile.

CONCLUSIONS

In conclusion, our findings demonstrate that the level of AOP during BFR has a small but significant effect on the Vel_{MED} at 60% of 1RM for both BP and SQ exercises. Specifically, our results suggest that from ~80% occlusion, Vel_{MED} improved markedly for BP exercise and ~100% for SQ exercise, compared to sets completed without occlusion. These findings have practical application for strength and conditioning specialists because our results suggest that superimposed BFR at 80% of AOP allowed an acute neuromuscular potentiation of execution velocity.

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Conflict of interest

The authors declare that they have no competing interests.

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Does beta-alanine supplementation enhance adaptations to resistance training? A randomized, placebo-controlled, double-blind study

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ABSTRACT: The aim of the present study was to assess the effects of beta-alanine supplementation on muscle strength and thickness. Nineteen resistance-trained men (age: 27.3 ± 5.5 years; height: 178 ± 10 cm; body mass: 83.4 ± 9.7 kg; training experience: 5.9 ± 3.9 years) were allocated to one of the following groups: Beta-alanine (BA) (6.4 g/day of beta-alanine) or Placebo (PLA) (6.4 g/day of maltodextrin). Subjects completed 4 resistance training sessions per week for 8 weeks. The following assessments were performed before and after intervention periods: 1 repetition maximum (1RM) and 60%1RM tests in the bench press (60%1RM_{BENCH}) and back squat (60%1RM_{SQUAT}) exercises; muscle thickness assessment of biceps brachialis (MT_{BB}), triceps brachialis (MT_{TB}), and vastus lateralis (MT_{VL}) by ultrasonography. No significant difference between groups was observed for the absolute increase (pre-post intervention) in the 1RM_{BENCH} (mean difference = 0.8 kg; $p = 0.679$), 1RM_{SQUAT} (mean difference = 0.1 kg; $p = 0.992$), MT_{BB} (mean difference = 0.7 mm; $p = 0.637$), MT_{TB} (mean difference = 1.4 mm; $p = 0.282$), MT_{VL} (mean difference = 1.6 mm; $p = 0.311$), 60%1RM_{BENCH} (mean difference = 0.5 repetitions; $p = 0.670$) and 60%1RM_{SQUAT} (mean difference = 0.7 repetitions; $p = 0.690$). In conclusion, the 8-week training period induced significant strength and morphological responses. However, the addition of beta-alanine supplementation did not enhance these adaptive outcomes.

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INTRODUCTION

Anaerobic glycolysis is the predominant energy source during high-intensity exercise, which induces increased intracellular accumulation of hydrogens ions (H^+) [1]. This phenomenon, in turn, may result in decreased intramuscular pH, leading to muscle fatigue and, consequently, impaired neuromuscular performance [2]. Therefore, improving the cell's ability to buffer H^+ may offer an advantage in the management of fatigue and a subsequently improved capacity to perform high-intensity activities. Consequently, sports practitioners and researchers often test different ergogenic aids (e.g., sodium bicarbonate and beta-alanine [BA]) that could enhance the performance and adaptive responses during high-intensity exercises by providing an augmented buffering potential.

Carnosine is an intracellular dipeptide located in the cytoplasm, especially in skeletal muscle cells, where it is synthesized from the amino acids L-histidine and BA [3, 4]. Higher muscle carnosine content has been shown to attenuate fatigue during exhaustive dynamic exercise [5] and induce higher calcium sensitivity of the

contractile apparatus [6]. However, carnosine synthesis is limited by BA availability, since skeletal muscle cells have a high L-histidine content [4]. The chronic supplementation of BA between 4 and 24 weeks appears to be safe [7] and can increase skeletal muscle carnosine content by up to 200% [8], with strong evidence supporting the ergogenic role of supplementation in exercises ranging from 30 s to 10 min in duration [9].

Due to the anaerobic nature of resistance training (RT), one can suggest that BA supplementation may present a potential ergogenic aid for practitioners. Most studies that adopted a supplementation protocol alongside RT programmes assessed maximal strength, power, and strength endurance outcomes [10, 11]. However, to our knowledge, no previous study has investigated the effects of BA on morphological adaptations of specific muscles, with only indirect measures of total lean mass (e.g. whole-body dual-energy X-ray absorptiometry) being adopted to the present date [10, 12, 13]. Therefore, the present study aimed to assess the chronic effects of BA

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supplementation on strength and hypertrophy outcomes in RT men. Our initial hypothesis was that the supplementation protocol adopted would maximize both strength and morphological adaptations induced by the RT programme.

MATERIALS AND METHODS

Participants

Twenty healthy males (age: 27.4 ± 5.3 years; height: 178 ± 10 cm; total body mass: 83.4 ± 9.7 kg; RT experience: 5.9 ± 3.9 years) who were recruited from a resistance-trained population participated in the study. A minimum final sample size of 20 participants was required according to a priori power analysis where the vastus lateralis muscle thickness was assessed as the outcome measure with a target effect size difference of 0.75, an alpha level of 0.05 and a power ($1 - \beta$) of 0.80 [14]. Volunteers performed RT (minimum frequency of once a week) and all exercises adopted in the training intervention and the strength tests for at least 1 year before entering the study. In addition, participants stated that they were not consuming any dietary supplements that could enhance performance for a minimum of 6 months before the start of the study and presented relative one repetition-maximum (1RM) values of 1.25x and 1x total

body mass in parallel back squat and bench press exercises, respectively [15]. Although 20 volunteers initiated the experiment, 1 from the BA group was excluded from the analysis due to a training frequency lower than 85%. Therefore, BA and PLA groups had 9 and 10 subjects, respectively (Figure 1). This study was approved by a university research ethics committee (protocol 2.094.534) and was conducted in accordance with the Declaration of Helsinki. All subjects read and signed an informed consent document.

Experimental protocols

The study followed a randomized, placebo-controlled, double-blind design [16]. Participants were matched for strength, based on their relative one maximum repetition (1RM) bench press and parallel back squat scores, and subsequently randomly allocated to receive either beta-alanine (BA) or placebo (PLA) supplementation. The experimental period lasted 10 weeks: 1st week – familiarization period and pre-intervention assessments (baseline); 2nd–9th weeks – training and supplementation intervention period; 10th week – post-intervention assessments. Assessments of maximal dynamic muscle strength (1RM test for bench press and parallel back squat exercises), muscular endurance (maximum repetitions at 60% of 1RM test for bench

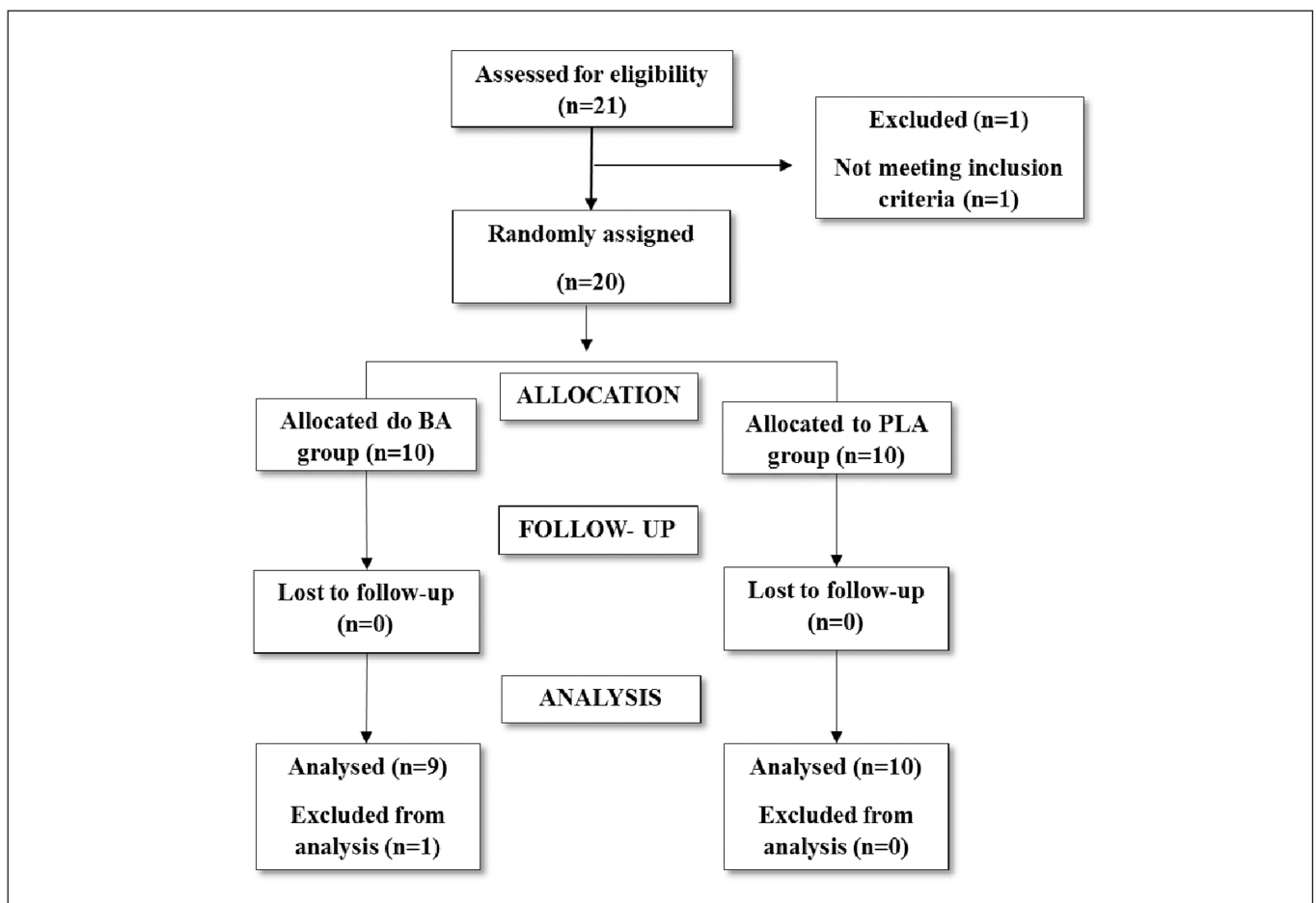


FIG. 1. Subject recruitment and flow through the protocol. BA (beta-alanine); PLA (placebo).

press and parallel back squat exercises), and muscle thickness (ultrasound) were performed at both pre- and post-intervention time points.

Supplement schedule

Participants received either β -alanine (99.9% pure β -alanine, non-sustained release formula; CarnoSyn, NAI, San Marcos, California, USA) or a placebo (maltodextrin, Neonutri, Pocos de Caldas, Minas Gerais, Brazil) 4 times per day (4 doses of 1.6 g each [total of 6.4 g/day]), separated by 3–4 hours during the entire training intervention period (8 weeks) on both training and non-training days. This dosage was adopted based on previous studies that reported increases in muscle carnosine content following BA supplementation [10]. The capsules for both groups were similar in appearance, weight (400 mg), and taste. Enough supplement for 8 weeks was provided in an unlabelled and sealed pot separated by a researcher not involved in data collection. Adherence was determined by counting the amount of supplemental capsules remaining at the post-supplementation period. A minimum of 85% compliance was required [11]. Any side-effects of supplementation (e.g., paraesthesia) were individually monitored during the study. If a participant forgot to take a dose, an additional dose in another period or on a different day was to be ingested to complete the total dose of 358.4 g by the end of the study.

Resistance training procedures

Before the training intervention period, all participants underwent 12-repetition maximum (12RM) testing (according to guidelines established by the National Strength and Conditioning Association [NSCA] [17]) to determine individual initial training loads for each exercise.

The RT protocol adopted was the same for both groups. During each intervention week, participants performed 4 weekly split routine sessions (A – Mondays and Thursdays; B – Tuesdays and Fridays); (pectoralis major, deltoids and triceps brachii in routine A; quadriceps, latissimus dorsi, and biceps brachii in routine B). Three sets were performed per exercise with a corresponding load of 12 RM, with 60 seconds of rest between sets and 120 seconds between exercises [18]. Participants were instructed to perform each set to the point of momentary concentric muscular failure. If more than 12 repetitions could be performed in the last set of a given exercise, increments in the external load ranging from 5% to 10% were implemented in the next training session. Training routines were supervised by the research team to monitor the proper technique and ensure the safety of the subjects.

Food intake estimation

To avoid potential confounding of outcomes induced by diet, subjects were instructed to maintain their usual nutritional regimen and to avoid taking any supplements during the intervention period. A 24-hour food recall on 2 non-consecutive weekdays and 1 day at

the weekend was adopted to assess dietary nutrient intake [19], which was analysed through NutWin software (UNIFESP, São Paulo, Brazil).

Muscle thickness (MT)

Measurements of MT were obtained through ultrasound imaging. All testing was performed by a trained technician through the use of an A-mode ultrasound imaging unit (Bodymetrix Pro System; Intelametric Inc., Livermore, CA, USA). A 2.5-MHz linear array ultrasound probe was placed perpendicular to the tissue interface without depressing the skin. High-quality images were saved to the hard drive and MT dimensions were obtained by measuring the distance from the subcutaneous adipose tissue–muscle interface to the muscle–bone interface [20]. Measurements of 3 sites were taken on the right side of the body: biceps brachii (MT_{BB}), triceps brachii (MT_{TB}), and vastus lateralis (MT_{VL}). The upper arm measurements were made while subjects were standing, and the thigh muscle measurements were taken through a lying supine position.

For MT_{BB} and MT_{TB} , measurements were obtained 60% distal between the lateral epicondyle of the humerus and the acromion process of the scapula. For MT_{VL} , measurements were taken at 50% of the distance between the lateral condyle of the femur and the greater trochanter. A henna ink mark (reinforced every week) was used to maintain consistency between pre and post-intervention testing. To ensure that MT values were not overestimated from muscle swelling, images were obtained at least 48 h after training sessions, for both pre- and post-intervention assessments [21].

Additionally, for each site, at least 3 images were obtained to ensure the accuracy of measurements. According to the methodology described by Brigatto et al. [15], if measurements were within 1 mm of one another the figures were averaged to obtain a final value. If measurements were more than 1 mm from one another, a fourth image was obtained, and the closest 3 measurements were then averaged. The test-retest intraclass correlation coefficient (ICC) values from our laboratory for MT_{TB} , MT_{BB} , and MT_{VL} were 0.998, 0.996, and 0.999, respectively. The coefficient of variation (CV) for these measures were 0.6, 0.4, and 0.6%, respectively. The standard error of the measurement (SEM) for these measures was 0.42, 0.29, and 0.41 mm, respectively.

Muscle strength

Upper- and lower-body maximum strength was assessed by 1RM testing in the bench press ($1RM_{BENCH}$) and parallel back squat ($1RM_{SQUAT}$) exercises. Subjects reported to the laboratory having refrained from any exercise at least 48 hours before baseline and post-intervention assessments. 1RM testing was consistent with recognized guidelines, as established by the NSCA [17]. The ICC, CV and SEM from our laboratory for $1RM_{SQUAT}$ were 0.989, 0.8% and 2.05 kg, respectively. The ICC, CV and SEM for $1RM_{BENCH}$ were 0.990, 0.7% and 1.95 kg, respectively.

Muscle endurance

Ten minutes after 1RM tests, participants performed as many repetitions as possible until muscle failure at 60% of 1RM load [22] on both the bench press (60%1RM_{BENCH}) and parallel back squat (60%1RM_{SQUAT}). A standardized cadence of 40 bpm was adopted for each assessment (Metronome Beats, Stonekick). The ICC, CV and SEM for 60%1RM_{SQUAT} from our laboratory were 0.910, 3.3% and 1.13 repetitions, respectively. The test-retest ICC, CV and SEM for 60%1RM_{BENCH} were 0.943, 2.3% and 0.83 repetitions, respectively.

Total load lifted (TLL)

TLL (sets $\times$ repetitions $\times$ external load [23]) was calculated from training logs filled out by the researchers for every RT session. The weekly TLL was calculated as the sum of all loads lifted during the RT sessions that week. Additionally, the Δ TLL described the difference in the TLL between weeks 8 and 1 (e.g., TLL in week 8 minus TLL in week 1). The data were expressed in kilogram-force units (kgf).

Statistical analysis

The normality and homogeneity of the variances were verified using the Shapiro-Wilk and Levene tests, respectively. The mean, standard deviation (SD) and 95% confidence intervals (CI) were used after the data normality was checked. To compare mean values of the descriptive variables, food intake variables, total capsules consumed, total RT sessions performed, Δ TLL week 8 minus week 1 between groups (BA vs PLA), and the absolute difference (pre-to-post changes) between groups in MT, 1RM and 60% 1RM, an unpaired t-test was used. A 2x2 repeated measures analysis of variance (ANOVA) (interaction groups [BA and PLA] $\times$ time [pre- vs post-intervention]) was used to compare the dependent variables (1RM_{BENCH}, 1RM_{SQUAT},

60%1RM_{BENCH}, 60%1RM_{SQUAT}, MT_{TB}, MT_{BB}, and MT_{VL}). Post hoc comparisons were performed with the Bonferroni test. Mauchly's test of sphericity was applied and the Greenhouse-Geisser epsilon correction was used when the sphericity criteria were not met. Effect sizes were evaluated using partial eta squared (η^2p), with < 0.06 , 0.06–0.14 and, > 0.14 indicating a small, medium, and large effect, respectively [24]. The adopted significance was 5%. Effect sizes were also estimated for pairwise comparisons using Cohen's *d*. The *d* results were qualitatively interpreted using the following thresholds: < 0.2 , trivial; 0.2–0.6, small; 0.6–1.2, moderate; 1.2–2.0, large; 2.0–4.0, very large and; > 4.0 , nearly perfect. Data analysis was performed using a modified statistical Excel spreadsheet [24] and SPSS-22.0 software (IBM Corp., Armonk, NY, USA). The figures were formatted in GraphPad Prism version 6.0 software (La Jolla, CA, USA).

RESULTS

No significant difference was observed between groups for any baseline measurement (Table 1). No significant difference was noted between groups for total capsules consumed (873.3 ± 44.9 [97.4 $\pm$ 5.0% of compliance] vs 850.4 ± 44.9 [94.5 $\pm$ 6.2% of compliance], BA vs PLA, respectively) and total training sessions performed (30.6 ± 1.1 vs 30.6 ± 1.7 , BA vs PLA, respectively) during the intervention period. Three out of 9 participants correctly guessed that they were taking BA, while 3 of 10 participants correctly guessed that they were ingesting a placebo.

Muscle thickness

A significant main effect of time ($F_{1,17} = 11.807$, $p = 0.003$, $\eta^2p = 0.410$), but not group $\times$ time interaction ($F_{1,17} = 0.216$, $p = 0.648$, $\eta^2p = 0.013$), was observed for MT_{BB}. No significant

TABLE 1. Baseline descriptive statistics for the BA and PLA groups (mean $\pm$ SD).

Variables	PLA (n = 10)	BA (n = 9)	P value
Age (years)	28.5 $\pm$ 5.5	26.1 $\pm$ 5.5	0.311
Body Mass (kg)	86.9 $\pm$ 11.1	81.2 $\pm$ 6.0	0.082
Height (cm)	177 $\pm$ 10	178 $\pm$ 10	0.472
RT experience (years)	6.1 $\pm$ 4.7	5.9 $\pm$ 4.7	0.392
RT frequency (sessions $\cdot$ wk ⁻¹)	5.0 $\pm$ 0.1	4.6 $\pm$ 0.5	0.583
Total number of sets (sets $\cdot$ wk ⁻¹)	91.8 $\pm$ 5.4	91.6 $\pm$ 4.3	0.915
Total energy intake (kcal)	2401 $\pm$ 339	2322 $\pm$ 300	0.762
Protein intake (g $\cdot$ kg ⁻¹)	1.6 $\pm$ 0.3	1.7 $\pm$ 0.3	0.823
Carbohydrate intake (g $\cdot$ kg ⁻¹)	4.1 $\pm$ 0.7	4.3 $\pm$ 0.8	0.934
Fat intake (g $\cdot$ kg ⁻¹)	0.5 $\pm$ 0.1	0.5 $\pm$ 0.1	0.928

PLA = placebo group; BA = beta-alanine group; RT = resistance training; sessions $\cdot$ wk⁻¹ = sessions per week; sets $\cdot$ wk⁻¹ = sets per week; kcal = kilocalories; g/kg⁻¹ = grams per kilogram of body mass.

between-group difference was noted for the absolute increase in MT_{BB} (pre- to post-intervention) (mean difference [95%CI] = 0.7 [-2.3 to 3.7 mm]; $p = 0.637$). The between-group effect size was small ($d = 0.22$) (Table 2).

For MT_{TB}, only a significant main effect of time ($F_{1,17} = 13.011$, $p = 0.002$, $\eta^2p = 0.434$), but not group $\times$ time interaction ($F_{1,17} = 1.253$, $p = 0.279$, $\eta^2p = 0.069$), was noted. No significant difference between groups was observed for the absolute increase (pre- to post-intervention) (mean difference [95%CI] = 1.4 [-1.2 to

4.1 mm]; $p = 0.282$). A small effect size ($d = 0.53$) between groups was revealed (Table 2).

A significant main effect of time ($F_{1,17} = 19.899$, $p < 0.001$, $\eta^2p = 0.539$), but not group $\times$ time interaction ($F_{1,17} = 1.073$, $p = 0.315$, $\eta^2p = 0.059$), was found for MT_{VL}, while no significant difference between groups was found for the absolute increase (mean difference [95%CI] = 1.6 [-1.6 to 4.9 mm]; $p = 0.311$). The between-group effect size was small ($d = 0.49$) (Table 2).

TABLE 2. Pre and post 8 weeks muscle morphology measures for the BA and PLA groups (mean $\pm$ SD).

Variables	Pre	Post 8 weeks	MD [95%CI]	time <i>P</i> value	time*group <i>P</i> value
MT _{BB} (mm)					
PLA	42.2 ± 8.6	45.0 ± 6.8*	2.8 [0.7 to 4.9]	0.011	0.648
BA	44.7 ± 4.5	46.9 ± 5.4	2.2 [-0.6 to 4.3]	0.056	
MT _{TB} (mm)					
PLA	39.1 ± 5.1	42.1 ± 4.1*	3.0 [1.1 to 4.9]	0.003	0.279
BA	39.7 ± 5.4	41.3 ± 5.1	1.6 [-0.3 to 3.5]	0.105	
MT _{VL} (mm)					
PLA	46.5 ± 9.9	50.8 ± 8.7*	4.3 [2.0 to 6.5]	0.001	0.315
BA	45.5 ± 6.3	48.2 ± 6.0*	2.7 [0.2 to 5.0]	0.030	

BA = beta-alanine group; PLA = placebo group; MT_{BB} = muscle thickness of the biceps brachii muscle; MT_{TB} = muscle thickness of the triceps brachii muscle; MT_{VL} = muscle thickness of the vastus lateralis muscle; MD = Mean Difference; CI = Confidence Interval. * $p < 0.05$ vs pre-intervention.

TABLE 3. Pre- vs. post-intervention muscle strength and muscle endurance measures for the BA and PLA groups (mean $\pm$ SD).

Variables	Pre	Post 8 weeks	MD [95%CI]	time*group <i>P-value</i>
1RM _{BENCH} (kg)				
PLA	109.8 ± 12.7	116.4 ± 10.6 [†]	6.6 [3.7 to 9.4]	0.679
BA	106.7 ± 11.8	112.4 ± 11.7 [*]	5.7 [2.7 to 8.7]	
1RM _{SQUAT} (kg)				
PLA	108.6 ± 11.8	127.2 ± 20.7 [*]	18.6 [8.0 to 29.1]	0.993
BA	106.4 ± 15.2	125.1 ± 20.7 [*]	18.7 [7.5 to 29.8]	
60%1RM _{BENCH} (rep)				
PLA	15.1 ± 1.7	17.2 ± 1.5 [*]	2.1 [0.6 to 3.5]	0.671
BA	16.8 ± 2.5	18.4 ± 2.5 [*]	1.6 [0.1 to 3.2]	
60%1RM _{SQUAT} (rep)				
PLA	19.1 ± 7.8	22.7 ± 6.0 [*]	3.6 [1.0 to 6.1]	0.690
BA	19.1 ± 5.2	22.0 ± 4.4 [*]	2.9 [0.2 to 5.5]	

PLA = placebo group; BA = beta-alanine group; 1RM_{BENCH} = one repetition maximum test in the bench press exercise; 1RM_{SQUAT} = one repetition maximum test in the back squat exercise; 60%1RM_{BENCH} = 60% of 1RM test in the bench press exercise; 60%1RM_{SQUAT} = 60% of 1RM test in the back squat exercise; MD = Mean Difference; CI = Confidence Interval. * $p < 0.05$ vs pre-intervention; [†] $p < 0.001$ vs pre-intervention.

Maximal strength

For 1RM_{BENCH}, only a significant main effect of time ($F_{1,17} = 40.062$, $p < 0.001$, $\eta^2 p = 0.702$), but not group $\times$ time interaction ($F_{1,17} = 0.177$, $p = 0.679$, $\eta^2 p = 0.010$), was revealed. For the absolute increase in 1RM_{BENCH}, no significant between-group difference was found (mean difference [95%CI] = 0.8 [-3.3 to 4.9 kg]; $p = 0.679$). A small effect size ($d = 0.20$) was observed between groups (Table 3).

A significant main effect of time ($F_{1,17} = 26.225$, $p < 0.001$, $\eta^2 p = 0.607$), but not group $\times$ time interaction ($F_{1,17} = 0.178$, $p = 0.993$, $\eta^2 p < 0.001$), was seen for 1RM_{SQUAT}. No difference was observed between groups for the absolute increase (pre- to post-intervention) (mean difference [95%CI] = -0.1 [-15.5 to 15.2 kg]; $p = 0.992$). The between-group effect size was only trivial ($d = -0.004$) (Table 3).

Muscle endurance

For 60%1RM_{BENCH}, only a significant main effect of time ($F_{1,17} = 14.122$, $p = 0.002$, $\eta^2 p = 0.454$), but not group $\times$ time interaction ($F_{1,17} = 0.187$, $p = 0.671$, $\eta^2 p = 0.011$), was found. For the absolute increase from baseline, no significant between-group

difference was noted (mean difference [95%CI] = 0.5 [-1.6 to 2.5 repetitions]; $p = 0.670$). A small effect size ($d = 0.20$) was observed between groups (Table 3).

A significant main effect of time ($F_{1,17} = 13.711$, $p = 0.002$, $\eta^2 p = 0.446$), but not group $\times$ time interaction ($F_{1,17} = 0.165$, $p = 0.690$, $\eta^2 p = 0.010$), was observed for 60%1RM_{SQUAT}. No between-group difference was noted for the absolute increase from baseline (mean difference [95%CI] = 0.7 [-2.9 to 4.4 repetitions]; $p = 0.690$). The between-group effect size was only trivial ($d = 0.19$) (Table 3).

Total load lifted

No difference between groups was observed for the sum of weekly TLL ($p = 0.610$; mean difference [95%CI] = 23978 [-6421 to 54378 kgf]) (Figure 2A) and Δ TLL week 8 - week 1 ($p = 0.102$; mean difference [95%CI] = 3067 [-17 to 6151 kgf]) (Figure 2B).

DISCUSSION

The present study aimed to assess the chronic effects of BA supplementation on muscle strength and morphology in RT participants undertaking an 8-week training programme. Refuting the initial hypothesis, the main finding was that BA supplementation did not maximize RT-induced adaptations.

Although a significant overall training effect was noted for muscle morphology, no significant difference was detected between groups for MT_{BB}, MT_{TB} and MT_{VL}. Divergent results have been reported by studies that assessed body composition outcomes with exercise plus BA supplementation combined [10, 13]. However, possible local adaptations had not been investigated yet. To our knowledge, this was the first study to assess MT outcomes following a BA supplementation and training protocol, which limits comparisons with previous investigations. Therefore, future studies assessing the possible effects of BA on MT are encouraged.

A positive training effect on 1RM strength was found from pre- to post-training, but no significant difference between groups was noted for both 1RM tests. Research to date about the effects of BA on maximal strength outcomes during an RT programme is limited. Our results corroborate previous investigations from Hoffman et al. [25] and Outlaw et al. [26]. The predominant phosphagenic nature of 1RM tests may explain the absence of effects of BA on this variable; their performance would not be limited by muscle acidosis [27]. Controversially, Maté-Munhoz et al. [28] and Hoffman et al. [12] described significant increments in 1RM following a supplementation protocol. However, differences regarding the RT protocol adopted and the use of additional ergogenic supplements (creatine in the study of Hoffman et al. [12]) during the intervention periods must be considered when attempting to explain the distinct results between the present study and the aforementioned ones. In addition, the increases in maximal strength observed by these investigations might have been an indirect effect of the increased training volume induced by BA supplementation.

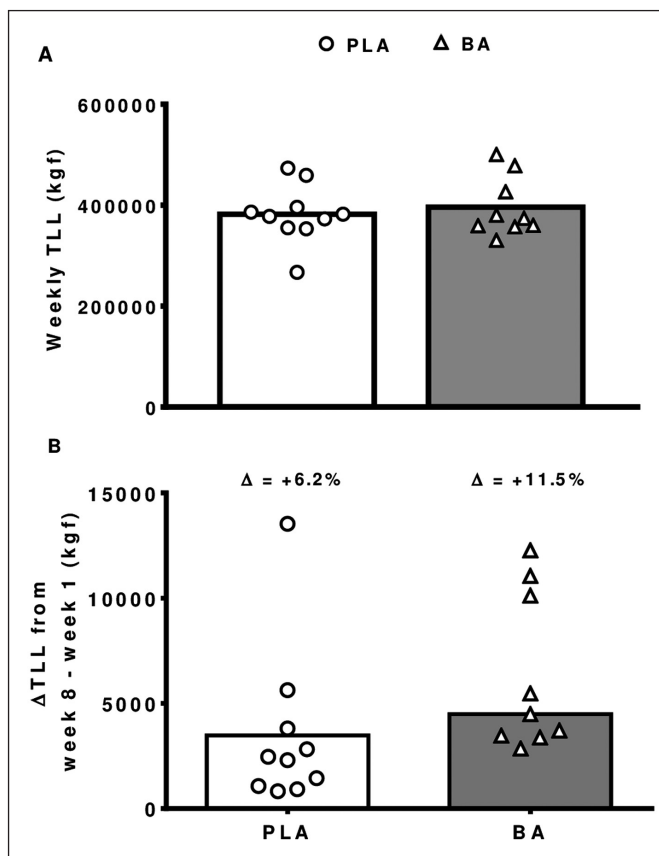


FIG. 2. Sum of weekly total loads lifted (TLL) in the BA and PLA groups during the 8-week training period (2A). The delta Δ and relative (%) changes in TLL measured at week 8 versus week 1 (2B). All $p > 0.05$.

Due to the buffering nature of an augmented muscle carnosine content, the initial hypothesis was that BA would induce increases in training volume, which, in turn, would result in significant strength and hypertrophic adaptations [29]. Our results corroborate findings from Bassinelo et al. [19], in which a 4-week supplementation protocol was not able to induce significant increases in the total training volume performed in both upper and lower limb exercises. Contrary to the current study, Hoffman et al. [12] reported increases in TLL in RT men for the barbell squat and bench press exercises following 10 weeks of supplementation. However, it should be noted that the TLL data from our study were reported as the sum of all exercises performed during the intervention weeks, while in the study of Hoffman et al. [12] only the TLL of 2 exercises was considered, although several exercises were performed during the training protocol. Thus, it is possible that, from an entire RT session standpoint, TLL might be less influenced by the supplementation. Increases in the TLL resulting from 3 weeks of BA supplementation were reported by the cross-over study of Hoffman et al. [25]. However, it is important to note that Hoffman et al. [25] adopted a short wash-out period (3 weeks) between conditions (with vs without supplementation), which probably did not allow muscle carnosine levels to fully return to the pre-intervention values [30], constituting a confounding factor and limiting inferences about the isolated effects of BA on training volume. Therefore, although speculative, the lack of effect of supplementation on strength and morphological adaptations observed may be attributed to the non-significant effects of BA on TLL outcomes.

For muscle endurance, our initial hypothesis was that, due to the glycolytic nature of strength endurance tests (and higher muscle acidosis) [19], BA supplementation would promote significant increases in the number of repetitions performed. Although the 8-week intervention period promoted significant increases in muscle endurance for both groups, the number of repetitions performed in the 60%1RM tests was not influenced by BA supplementation. Conflicting findings have been reported regarding BA and muscle endurance outcomes. While our results corroborate findings from Kendrick et al. [10] and Bassinelo et al. [19], other studies were able to detect additional effects on muscle endurance performance when supplementing BA [11, 26]. The characteristics of the participants [26] (gender, training experience) and the training protocol employed might help to explain these divergent results. In addition, based on the findings of Sale et al. [11] and Bassinelo et al. [19], isometric exercise tests may provide a more suitable means to test the hypothesis that an increase in muscle carnosine content (induced by

BA) improves exercise capacity and performance, due to enhanced muscle buffering. Moreover, the optimal exercise intensity to enhance anaerobic demand seems to be around 45% of the maximal isometric voluntary contraction [31], which suggests that the magnitude of acidosis induced by the 60%1RM test in the current study was not sufficient to impair performance.

Exercise duration has been identified as the main factor influencing the effectiveness of BA supplementation [9]. Previous meta-analytic data have reported no difference in the effect sizes between PLA and BA groups on exercising protocols lasting < 60 seconds [32], which may help to explain the lack of effects of BA on the exercise capacity and performance in the current study. Therefore, RT protocols characterized by a much higher number of repetitions (longer time under tension) and/or with shorter rest periods might, due to increased hydrogen ion accumulation and greater muscle acidosis, derive a more meaningful ergogenic effect from BA supplementation [28].

The main limitation of the study is that no methods were used to assess participants' muscular carnosine content, making it difficult to draw inferences about the influence of this variable on performance and morphological outcomes. In addition, it is important to note that the present results may not translate to other exercise modalities and populations, which may benefit from a supplementation protocol. Therefore, future studies with different characteristics regarding supplementation, participants' levels and training protocols are encouraged.

CONCLUSIONS

In conclusion, an 8-week RT programme promoted improvements in muscle size, strength and endurance capacity in RT men, but supplementation with 6.4 g of BA per day did not enhance these adaptations, relative to a PLA.

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Conflict of interest declaration

The authors declare have not potential conflict of interest in relation to this paper.

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Relationship between vertical jump tests and ice skating performance in junior Polish ice hockey players

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ABSTRACT: The aim of this study was to determine the relationships between vertical jumps (VJ) and various on-ice skating performances of junior ice hockey players ($n = 19$). The three modes of VJ or off-ice measures were countermovement jump with arm swing (CMJ), squat jump (SJ) and depth drop jump (DDJ). The on-ice skating performance was measured by the skating multistage aerobic test (SMAT), forward and backward acceleration test, top speed test, and repeated sprint ability (RSA) test. The relationships between the variables were quantified using Pearson's product-moment correlation. DDJ showed a significant positive correlation with forward average skating speed (FASS) ($r = 0.62$) and strong correlations with backward average skating speed (BASS) ($r = 0.81$), and maximum skating speed (MSS) ($r = 0.71$). SJ was found to be strongly correlated with BASS ($r = 0.82$) and MSS ($r = 0.76$), whereas the only on-ice performance that significantly correlated with CMJ was BASS ($r = 0.68$). All three modes of VJ were inversely and non-significantly correlated with performance decrement index and fatigue index, as determined by the RSA test. SMAT was not significantly correlated with either VJ or RSA. Correlations between all three modes of VJ tests were significant. Therefore, this study concludes that: (1) DDJ can be used as a predictor of all the ice skating speed tests, whereas SJ can predict BASS and MSS. CMJ, on the other hand, can predict the performance of only BASS. (2) RSA performance cannot be predicted from CMJ, SJ, or DDJ tests, and (3) neither any of the VJ nor RSA can predict skating endurance of junior ice hockey players.

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Squat jump
Depth drop jump
Skating multistage aerobic test
Repeated sprint ability
Maximum skating speed

INTRODUCTION

Intermittent high intensity bouts of skating, rapid changes in direction and velocity, individual skills, tactics, and motivation are some important requirements of playing ice hockey. On-ice performance is a primary requirement for an ice hockey player and thus relevant on-ice assessment is an important component of the training programme for them. However, many of the suggested sports-specific tests of ice hockey are off-ice, and are performed in well-equipped laboratories or any suitable facility. Agility in on-ice performance is also related to off-ice conditioning. Commonly performed off-ice tests for ice hockey players are the Wingate test, various jump tests, repeated sprint ability (RSA) tests, and sprint tests or time trial run [1–6]. The validity of some of the off-ice tests has been questioned for quantifying aerobic or anaerobic power related to ice hockey [7, 8]. Off-ice tests mostly focus on both anaerobic endurance and aerobic capacities of the players, although the earlier one is predominant.

Studies confirmed a significant relationship between running speed and on-ice sprinting ability in young male ice hockey players [2, 9]. Jump tests are widely used to assess fitness of ice hockey players,

and some of the jump tests are correlated with the performance of on-ice measurement [3, 4]. The jump test is used for measuring leg power and has repeatedly been shown to be related to skating abilities and ability to perform a wide range of simple and complex activities including throwing, sprinting, and change of direction [2, 4, 10]. Vertical jump is a part of the NHL combined test and very often is used not only as one of the gold standards, but as a simple off-ice test that can distinguish ice hockey potential [11, 12]. Vertical jumping is often considered as a basic movement skill, involves multi-joint movement and requires a higher level of motor coordination [2, 4]. The commonly used VJ test protocol varies widely. Countermovement jump with arm swing (CMJ), squat jump (SJ) and depth drop jump (DDJ) are the three major variations of VJ that were used in this study. Skating speed is one of the most desirable elements in ice hockey routinely assessed. Due to biomechanical similarities in movement patterns, strength and conditioning specialists recommend jumps and back squat exercise to improve ice skating performance [13].

Several previous studies focused on prediction of on-ice performance from off-ice tests [1, 2, 4, 8, 9, 13]. However, research focused on the relationship between various VJ tests and a wide range of on-ice performance, especially in junior ice hockey players, is scanty. Therefore, the primary purpose of this investigation was to determine whether any significant correlations exist between the (1) VJ tests and on-ice field tests, and (2) RSA and skating endurance (or SMAT) in junior Polish ice hockey players. It is hypothesized that DDJ is the single best off-ice VJ test in this study that predicts on-ice performance such as FASS, BASS, and MSS. Repeated sprint ability and SMAT, on the other hand, are not related to any of the VJ test performances.

MATERIALS AND METHODS

Subjects

Twenty-five outfield junior ice hockey players from the club UKS Zagłębie Sosnowiec of southern Poland participated in this study. Six players were excluded from the study after they failed to complete testing sessions. Of the final participants, 10 were defenders and 9 were forwards. Age, height, weight, and body mass index (BMI) of the players were 18.7 ± 2.2 years, 179.2 ± 11.6 cm, 77.8 ± 10.2 kg and 24.3 ± 1.9 , respectively. The team was participating in the youth hockey league (MHL) and Central Junior League (CLJ) of Poland. The participants were in the middle of their competitive period, participating in 5–6 training sessions per week that comprised technical, tactical, fitness and strength training. The experimental protocol and potential risks involved in the study were described to all the participants and they were allowed to withdraw from any stage of the study without providing any reason. Participants, or their parents (in the case of < 18-year-old participants), gave voluntary written informed consent to participate in the study. The study was approved by the Ethics Committee of the Jerzy Kukuczka Academy of Physical Education in Katowice (No. 8/2018).

Study design

This study was conducted over 4 days and on all the occasions the players were tested under similar experimental conditions and at the same time of day (6 to 9 p.m.). None of the volunteers ate food in the last 3 hours before testing, but water was allowed to drink. Participants were instructed to maintain normal dietary and fluid intake and to abstain from training and any other heavy physical activity for 24 hours before testing. Intake of coffee or any caffeine-containing beverages in the last 12 hours before the experiment was not allowed.

The whole study was conducted in two major stages – (1) off-ice VJ tests and (2) on-ice tests. The off-ice VJ tests conducted were CMJ, SJ, and DDJ. All off-ice VJ tests were conducted in the Laboratory of Analysis in Sports of the Jerzy Kukuczka Academy of Physical Education in Katowice (Poland). The four on-ice tests were – (i) skating multistage aerobic Test (SMAT or beep test), (ii) forward and backward acceleration test, (iii) top speed test, and (iv) repeated sprint ability (RSA) test. All the on-ice tests were conducted on

the ice rink of Stadion Zimowy in Sosnowiec, Poland. All the on-ice and jump tests were explained and supervised by the same strength and conditioning specialist of the team. All the on-ice performances were tested wearing full ice hockey equipment with an ice hockey stick in their preferred hand.

Vertical jump (VJ) tests

The subjects performed a warm-up, as instructed by the coach, just before performing the actual jump tests. All the jump tests were performed on the OptoJump (Microgate, Bolzano, Italy), an optical data acquisition system. The OptoJump is able to measure all air- and ground-related times with precision to 1/1000 of a second [14]. All subjects completed 3 trials for each jump test and the highest jump was recorded. Between two trials, a 1-min rest period was allowed. All the VJ tests were performed without any familiarization session. In order to control for the testing order effect, the order in which the players performed jump tests was randomized [15, 16].

Countermovement jump with arm swing (CMJ)

The subject stood comfortably, bent his knees, hips and ankles, with his hands at his sides. Thereafter he was instructed to swing his arms forward when he jumped vertically. The countermovement started when the legs were bent down to 90°. A pre-jump or step was not allowed. Bending the knees before landing or kicking the legs forward by flexing at the hip was not allowed and the jump was repeated [17, 18].

Squat jump (SJ)

The subject was instructed to stand with his hands on his hips and to bend at the knees, hips, and ankles. After he became motionless, the tester instructed him to jump. The player jumped as high as possible keeping his hands on his hips and his legs straight [19].

Depth drop jump (DDJ)

The subject stood on a jump box of 45 cm height, behind the OptoJump. He was then instructed to step off towards the OptoJump optical measurement system in one motion and performed a maximal effort double-leg vertical jump, using an arm swing upon landing. The subject was instructed to quickly reverse the downward movement of the body to an upward movement in order to minimize the contact time with the ground upon landing, and maximize take-off velocity [20].

Skating Multistage Aerobic Test (SMAT)

This on-ice test for the prediction of $\dot{V}O_{2\max}$ was designed by Leone et al. [21]. The test was conducted on a 45 m course defined with markers at both extremities of the indoor ice hockey rink (Figure 1). The participant skated, holding the hockey stick with the preferred single hand, from one end to the other with a predefined speed, and then the speed was gradually increased until the participant was unable to maintain the speed anymore (about 3 m before a marker

after the sound signal). The pace was dictated by audible signals emitted by a calibrated audio player. The initial skating speed was set at $3.5 \text{ m} \cdot \text{s}^{-1}$, which was increased stepwise by $0.2 \text{ m} \cdot \text{s}^{-1}$. A 30 s rest period was allowed before beginning the next stage. The sound signals provided guidance to synchronize skating velocity with markers located at the midpoint (22.5 m) and both extremities of the 45 m course. At the start of each stage the participant player rested upright with the front skate parallel to the starting line. $\text{VO}_{2\text{max}}$ was estimated from a table based on the formula [21]:

$$\text{VO}_{2\text{max}} = 22.368 \times (\text{maximal velocity}) - 58.618$$

Forward and backward acceleration (0-5-10-30 m) test

The subjects were required to start from the goal line and skate forward with maximal effort for 30 m distance on a straight line (Figure 2). All subjects performed this test twice, with a break of 10 min, and the fastest performance was recorded. During the break between two trials, players followed self-selected low intensity active recovery [13].

After a break of 15 min rest, backward skating was performed from the same starting line. The protocol of forward and backward skating was similar. Both the forward and backward skating started after the player remained at standstill close to the starting line. The forward and backward skating time and velocity were measured using a photocell automatic laser timing system (Microgate, Racetime 2, Bolzano, Italy). The starting and finishing sensors were placed 30 m apart on the ice. Sprint time was measured to the nearest 0.01 s. Photocells were set at 0, 5, 10, and 30 m distance. Average speed while skating forward was designated as forward average skating speed (FASS), and similarly, the average speed attained while skating backward was called backward average skating speed (BASS).

Top speed test (50 ft flying top speed test)

Players were instructed to take their standing position on the goal line. The trial was started by skating toward the opposite goal line and around the net in an anticlockwise fashion toward the sprint

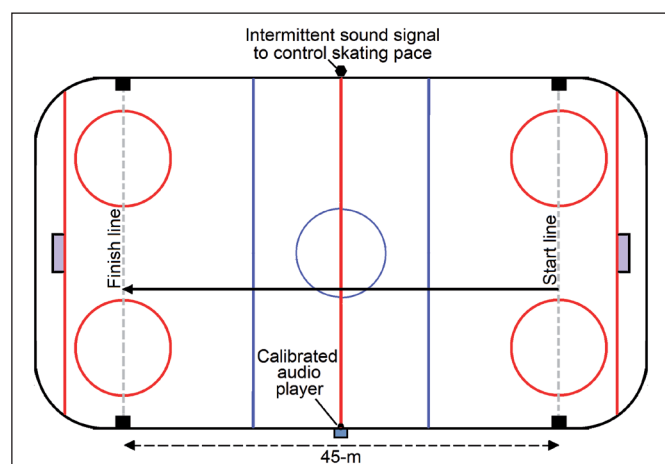


FIG. 1. Diagram of Skating Multistage Aerobic Test (SMAT) layout [21].

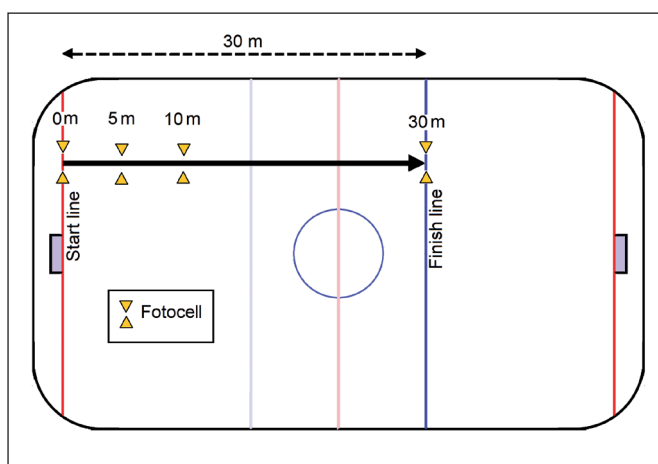


FIG. 2. Setup for the forward and backward acceleration (0-5-10-30 m) test.

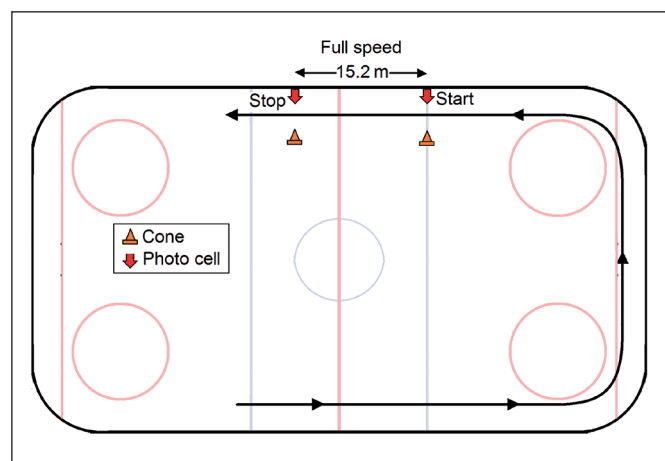


FIG. 3. Setup for the top speed test.

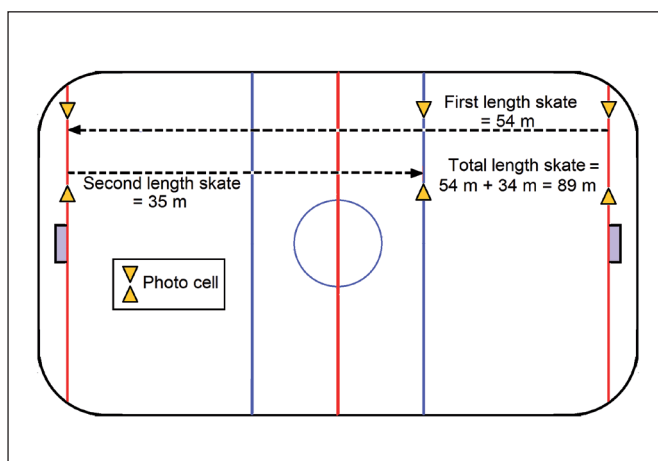


FIG. 4. Schematic of the 6 x (54+35)-m repeated sprint ability (RSA) test.

line. An automatic laser timing system (Microgate, Racetime 2, Bolzano, Italy) measured the maximum speed while skating. The starting and finishing sensors were set on the opposing blue lines 50 ft apart (Figure 3). Time to calculate top speed was measured to the nearest 0.01 s. One trial was performed crossing over to the right and the other crossing over to the left. Rest time between sprints was 6 minutes, during which the player performed stretching and very light activities only [13].

Repeated sprint ability (RSA) test [$6 \times (54 + 35) \text{ m}$]

This test involved sprinting an 89 m skating course – goal line to goal line (54 m) and back to the blue line (35 m) – as quickly as possible, and then returning to the starting line slowly. This was repeated 6 times, with 30 s recovery including the slow skating time required to return to the starting line. Figure 4 illustrates the course of skating of RSA. Subjects performed 5 minutes of individualized warm up before testing. All times were recorded by a set of photocells (Microgate Racetime 2, Bolzano, Italy). Fatigue index (FI) was calculated as follows [22]:

$$\text{FI} = (\text{mean sprint time} - \text{fastest sprint time}) / \text{fastest time} \times 100 (\%)$$

Statistical analyses

The descriptive statistics for all dependent variables were expressed by their means and standard deviations (mean $\pm$ SD). The reliability of all VJ tests were assessed using intraclass correlation analysis (ICC_{2,1}) with 95% confidence intervals ($\pm$ 95 CI). The coefficients obtained for CMJ, SJ, and DJ were 0.948 (0.794–0.981), 0.922 (0.809–0.967) and 0.913 (0.725–0.967), respectively. One-way analyses of variance were used to identify the statistical significance of the differences between vertical jumps. Tukey's post-hoc tests were employed to determine the level of significance when a significant F-ratio was found. Homogeneity of variance was examined by conducting Levene's test. The Pearson product-moment correlation coefficient was used to examine the relationship between off-ice and on-ice performance variables. The magnitude of the correlations was determined using the following criteria: trivial: 0 to 0.10, small: 0.11 to 0.3, moderate: 0.31 to 0.50, large: 0.51 to 0.70, very large: 0.71 to 0.90, and almost perfect: 0.91 to 1.00 [23]. Stepwise multiple regression was used to estimate on-ice performance variables by VJ (CMJ, SJ, DJ). All statistical analyses were conducted using Statistica 13.3 (TIBCO Software Inc., Palo Alto, CA, USA) and all graphics were plotted with the Sigma Plot version 12.0 and R software (R version 4.0.3, The R Foundation for Statistical Computing, Vienna, Austria). A level of $p \leq 0.05$ was selected for statistical significance.

RESULTS

Physical and physiological characteristics of the subjects, and the speeds they attained during on-ice speed tests (forward and backward acceleration test and top speed test), are presented in Table 1. $\text{VO}_{2\text{max}}$ was estimated from SMAT as described. Both forward and backward

TABLE 1. Physical and physiological characteristics of the subjects and skating speeds during on-ice speed tests.

Variables	Mean $\pm$ SD
Physical characteristics	
Age (y)	18.7 $\pm$ 2.2
Height (cm)	179.2 $\pm$ 11.6
Weight (kg)	77.8 $\pm$ 10.2
BMI ($\text{kg} \cdot \text{m}^{-2}$)	24.6 $\pm$ 1.9
$\text{VO}_{2\text{max}}$ ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$)	69.5 $\pm$ 4.7
Forward skating speed at distance zones	
0–5 m ($\text{km} \cdot \text{h}^{-1}$)	18.91 $\pm$ 1.10
5–10 m ($\text{km} \cdot \text{h}^{-1}$)	19.96 $\pm$ 0.91
10–30 m ($\text{km} \cdot \text{h}^{-1}$)	30.84 $\pm$ 1.13
0–30 m ($\text{km} \cdot \text{h}^{-1}$)	25.72 $\pm$ 0.92
Backward skating speed at distance zones	
0–5 m ($\text{km} \cdot \text{h}^{-1}$)	15.98 $\pm$ 1.52
5–10 m ($\text{km} \cdot \text{h}^{-1}$)	17.26 $\pm$ 1.42
10–30 m ($\text{km} \cdot \text{h}^{-1}$)	25.79 $\pm$ 1.43
0–30 m ($\text{km} \cdot \text{h}^{-1}$)	21.83 $\pm$ 1.30
Maximum skating speed attained at 50-ft top skating speed test	
Maximum speed ($\text{km} \cdot \text{h}^{-1}$)	35.10 $\pm$ 1.67
Duration at maximal speed (s)	1.54 $\pm$ 0.07

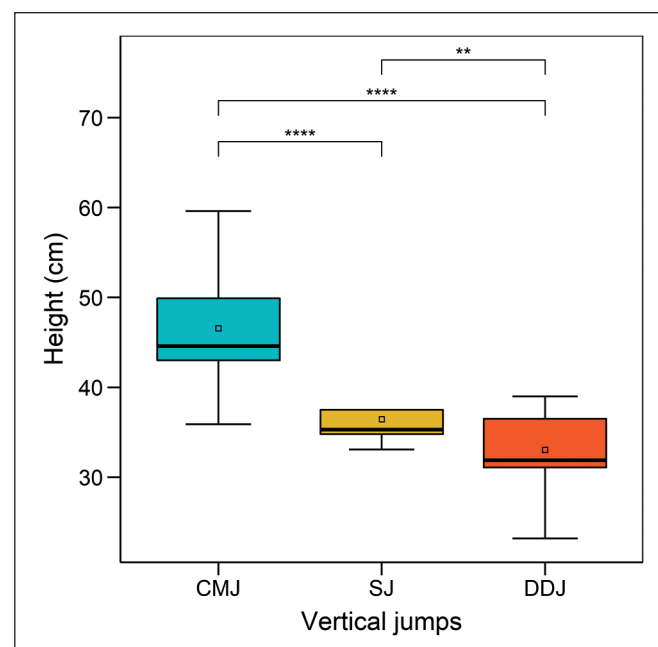


FIG. 5. Jump test performance of the subjects.

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$.

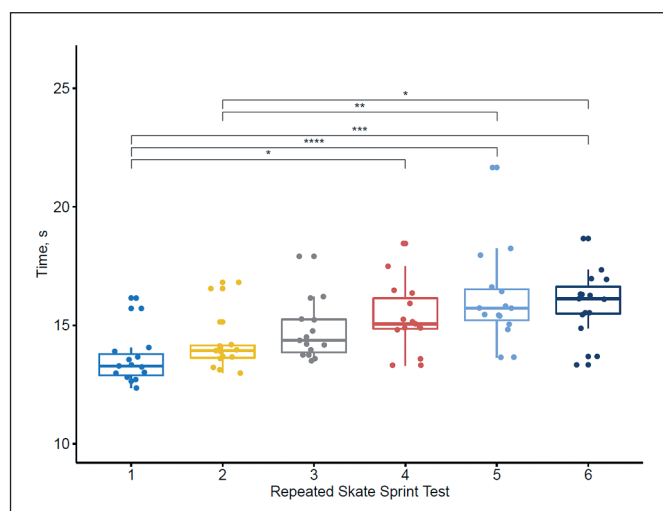


FIG. 6. Duration of sprint bouts in repeated sprint ability test [6 x (54+35)-m] on ice.

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$.

skating speeds were highest in the 10 to 30 m distance range and lowest in the 0 to 5 m range. Forward average skating speed was 17% to 21% faster than BASS at different photocell distance markings.

Performance of all the jump tests, expressed in centimetres, is presented graphically in Figure 5. Countermovement jump score was the highest, followed by SJ and DDJ.

Figure 6 shows the time required by the volunteers to complete each of the 6 skating sprints of the RSA test. The sprint time was shortest (13.19 ± 0.51 s) in the first bout, gradually increased thereafter, and was longest in the last (6th) bout (15.8 ± 1.97 s). The difference of the duration (and, thus speed) between any two consecutive bouts was non-significant. Statistical significance between sprint bouts and corresponding p-values are also presented in Figure 6.

Correlations between all the off-ice and on-ice performance of the subjects are presented in Figure 7. Countermovement jump shows a moderate correlation ($r = 0.68$, $p < 0.05$) with BASS but has no statistically significant correlation with any other ice skating fitness

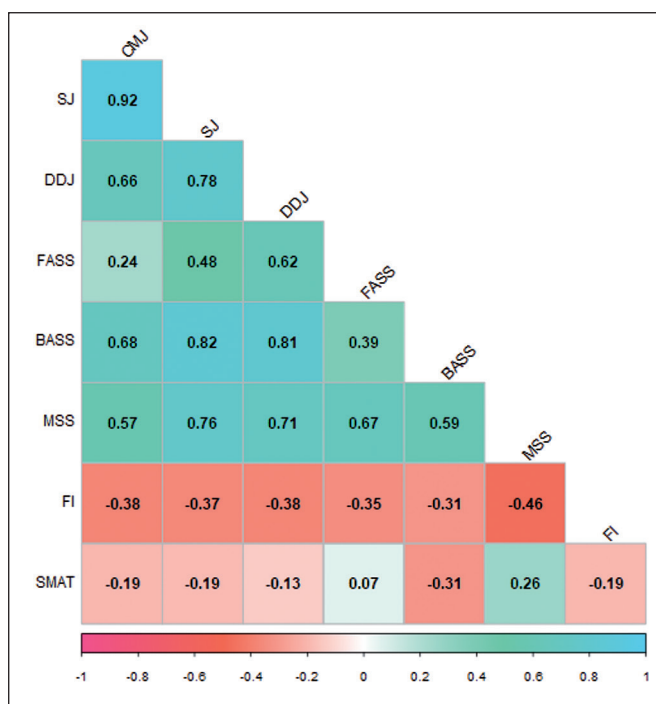


FIG. 7. Correlations between various performance variables in ice hockey players.

variables. Squat jump shows a strong correlation with both BASS ($r = 0.82$, $p < 0.01$) and MSS ($r = 0.76$, $p < 0.01$). Depth drop jump, on the other hand, shows moderate to strong correlations with all the skating speeds – FASS ($r = 0.62$, $p < 0.05$), BASS ($r = 0.81$, $p < 0.01$), and MSS ($r = 0.71$, $p < 0.01$). Performance decrement index (PDI) and fatigue index (FI), as calculated from RSA performance, are 11.07 ± 4.06 and 10.84 ± 3.47 , respectively. Neither PDI nor FI shows a significant relationship with any of the off- or on-ice variables.

Correlations between all the VJ performances are significant; especially the correlation between CMJ and SJ is very strong ($r = 0.92$, $p < 0.001$). No valid relationship ($r = 0.39$) between FASS and

TABLE 2. Regression equations to predict on-ice performance from vertical jump tests.

Equations	R	R ²	SEE	p-value
FASS 5 (km/h) = $-0.291 \text{ CMJ (cm)} + 0.513 \text{ SJ (cm)} + 13.883$	0.686	0.471	1.233	0.057
FASS 30 (km/h) = $0.128 \text{ DJ (cm)} + 21.599$	0.619	0.384	0.769	0.032
MSS (km/h) = $0.246 \text{ SJ (cm)} + 25.965$	0.760	0.577	1.106	0.004
BASS 10–30 (km/h) = $0.177 \text{ DJ (cm)} + 0.047 \text{ CMJ (cm)} + 17.600$	0.889	0.790	0.640	0.009
BASS 30 (km/h) = $0.129 \text{ SJ (cm)} + 16.527$	0.825	0.680	0.474	0.006

Note: FASS, forward average skating speed; BASS, backward average skating speed; MSS, maximum skating speed; R, multiple correlation coefficient; R², multiple R-Squared; SEE, standard error of estimate.

BASS was found. SMAT (or predicted $\text{VO}_{2\text{max}}$) was not found to be significantly correlated with any of the jump tests or with RSA, FASS, BASS, or MSS.

Based on the values obtained during VJ and on-ice tests, regression equations establishing the relationship between VJ and selected on-ice tests were determined by multiple regression analysis. Table 2 presents only those regression models for which the stochastic equation parameters are statistically significant. Regression analysis shows that CMJ and SJ are the best predictors for FASS over the first 5 m. Depth drop jump, on the other hand, predicts FASS over the distance of 30 m best. In the case of MSS, regression analysis reveals that SJ is an important predictor. Both DDJ and CMJ are the two valid indicators of BASS at the distance range of 10–30 m, whereas SJ can successfully predict backward skating performance (i.e., BASS) of the players over the distance of 30 m.

DISCUSSION

The aim of this study was to quantify the association mainly between VJ and ice skating performance in junior ice hockey players. The key finding of this study is that the VJ performance is a good indicator of ice skating speed of junior ice hockey players although each of the three VJ studied has a different magnitude of correlation with skating performance. The DDJ is significantly correlated with all skating speeds – forward, backward, and maximum. Squat jump performance can predict BASS and MSS, whereas CMJ is only significantly correlated with BASS. Another important finding is that the RSA cannot be predicted either from any of the VJ tests or from aerobic fitness alone.

The major purpose of this study was to determine the specific vertical jump test(s) which is/are most appropriate to predict on-ice performance of junior ice hockey players. Strong explosive power in the legs is one of the prerequisites for success in ice hockey players [19, 24, 25]. This is required to skate fast in all possible directions, quick acceleration and deceleration, change of direction, blocking opponent players, and hitting the puck with the hockey stick. Unlike many other team sports, jumping is not a very common activity in the sport of ice hockey. However, various jump tests are commonly used to measure strength and explosive power of leg muscles. Vertical jump tests are probably the most widely used jump tests to evaluate the effectiveness and progression of training, and selection of talents [10].

A strong correlation ($r = 0.92$) between CMJ and SJ, as observed in this study, is highly expected because many of the primary muscles involved in both the jumps are common. However, their differences cannot be ignored either. Knee extensor muscles have been indicated as the primary muscles involved in SJ [26, 27], whereas ankle planter flexors, in addition to knee extensors, are considered as the primary muscles for CMJ [27, 28]. The lateral gastrocnemius muscle has been shown to be one of the strongest predictors of all the VJ – CMJ, SJ, and DDJ [29]. Depth drop jump performance can be influenced by the jump heights (e.g., 20, 40, 60 cm) [30].

In this study it was found that VJ, especially DDJ, was correlated with all the skating speed performances, but not with RSA. Vertical jump provides a reliable measure of strength and explosive power of lower limb muscles, especially muscles associated with ankle, knee, and hip joints [31, 32]. A number of anthropometric, biomechanical, and physiological factors regulate VJ performance [33, 34]. Joint angle, velocity of muscle contraction, centre of mass height, air resistance, acceleration, and momentum are some of the biomechanical factors regulating VJ. Powerful contraction of muscles such as extensors, gluteus maximus, quadriceps, hamstrings, gastrocnemius, and soleus push the body against gravity by ground reaction during VJ [35, 36]. Good muscle flexibility, especially in males, can positively influence VJ by accommodating the imposed stress more easily and efficiently [33]. The leading physiological determinants of VJ measurement are muscle fibre composition, phosphagen storage, and concentration of some specific enzymes in the muscles [35, 36].

The SJ and DDJ, in the present study, were moderately to strongly correlated with forward and backward average skating speed and maximal skating speed. Although these jumps are biomechanically different from ice skating, they involve many of the same leg muscles and share a similar underlying basis of power generation [2]. A number of other studies [3, 4] have shown a strong correlation between squat jump and skating speed. However, the results of Behm *et al.* [37] did not find any significant relationship between squat jump and skating speed, probably because of use of only two-thirds of the rink for the speed test, which was not enough to build up maximum speed. In their study, Behm *et al.* [37] did not find any relationship between drop-jump (a form of DDJ) and skating speed, because the period of contact with the ground was too short. Skating during playing ice hockey involves longer contact times, and unlike the drop jump, greater emphasis on impulse. Depth drop jump in this study was strongly correlated with FASS, BASS, and MSP. Longer contact time upon landing may be one of the reasons for such significant correlations.

All the vertical jumps in this study show a poor relationship with RSA time (nonsignificant in all cases). Vertical jumps in the laboratory are largely dependent on the explosive power and strong leg muscles, whereas FI, an RSA indicator, is strongly dependent on both anaerobic and oxidative systems of the ice hockey players. However, significant correlations between VJ and RSA performance have been found by some researchers [38, 39]. Countermovement jump was found to be significantly correlated with RSA by Buchheit *et al.* [40]. Similarly, a positive correlation between squat jump and 10-m shuttle run sprint performance was found by Wisløff *et al.* [39]. SMAT performance is mainly determined by the capabilities of the aerobic metabolism and not much influenced by the explosive power of the leg muscles or efficiency of anaerobic metabolism. This may explain why the SMAT results are not correlated with VJ or RSA test results.

The investigated on-ice and off-ice skills are only a few of many determinants of the complex performance of a hockey player. One-time testing and reliability of the results are other limitations of the

study. This study also did not focus on the playing position-specific experimental response of the players. This was due to time-limited organizational options of the research file. Although a number of studies, including EMG, revealed involvement of principal leg muscles in VJ, much of the information is still incomplete [27]. More specific laboratory and field studies are required that can reveal the role of leg muscles responsible for the remarkable correlation between off-ice and on-ice tests. Besides leg muscles, VJ requires coordinated activities of several other muscles in the trunk and arms. Future research should seek to reveal the role of these muscles in playing ice hockey, and appropriate laboratory and field tests that can predict on-ice performance of the players should be designed.

Practical applications

The DDJ test, using a 45-cm high jump box, is the most reliable predictor of all three types of ice skating speeds – FASS, BASS, and MSS. Squat jump and CMJ tests can also predict some of the ice

skating speeds. We recommend that CMJ, SJ, and DDJ tests can be used appropriately as off-ice tests on junior ice hockey players to predict their on-ice performance. The RSA test is commonly used to estimate anaerobic endurance of ice hockey players, but none of the VJ tests nor an endurance test like SMAT can be used to predict fatigue in ice hockey players. Backward average skating speed is about 18% slower than FASS, and this can help guide coaches to plan defence and attack phases of ice hockey matches. According to the findings of this study, the correlations between the test results may guide training plan design and follow-up in junior ice hockey players.

Conflicts of Interest

The authors declare no conflict of interest.

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A review of machine learning applications in soccer with an emphasis on injury risk

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ABSTRACT: This narrative review paper aimed to discuss the literature on machine learning applications in soccer with an emphasis on injury risk assessment. A secondary aim was to provide practical tips for the health and performance staff in soccer clubs on how machine learning can provide a competitive advantage. Performance analysis is the area with the majority of research so far. Other domains of soccer science and medicine with machine learning use are injury risk assessment, players' workload and wellness monitoring, movement analysis, players' career trajectory, club performance, and match attendance. Regarding injuries, which is a hot topic, machine learning does not seem to have a high predictive ability at the moment (models specificity ranged from 74.2%-97.7%. sensitivity from 15.2%-55.6% with area under the curve of 0.66–0.83). It seems, though, that machine learning can help to identify the early signs of elevated risk for a musculoskeletal injury. Future research should account for musculoskeletal injuries' dynamic nature for machine learning to provide more meaningful results for practitioners in soccer.

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INTRODUCTION

As a branch of artificial intelligence, machine learning is being used in medicine and health sciences for some years [1, 2]. Though, machine learning is still quite new in sports science, sports medicine [3, 4] and particularly in soccer science. Machine learning use is based on the assumption that the computer and the algorithms will learn as we feed them with more data. Following data collection and data cleaning, the algorithms can build relationships among variables either without (unsupervised learning approaches) or with human assistance (supervised), who provide them with the cut-off values for specific variables. Through repeated data feeding, the computers and the algorithms will learn and will be able to identify and select, among the big number of variables, those that account for the dependent variable [3, 5, 6, 7].

One of the first studies with machine learning in soccer was published in 2014 [8]. It was focused on evaluating the technical and tactical abilities of teams during the UEFA EURO2012. Since that time, several papers have been published in soccer, focusing

on machine learning and injury prediction, physical performance prediction, training load and monitoring, players' career trajectory, club performance, and match attendance (Table 1). There are also papers on soccer match results prediction and betting, but these are not within the present review's scope. Despite the increasing number of research papers on machine learning use in soccer, it is still unclear what machine learning does, what it can offer to soccer clubs now and in the future, and how scientists and practitioners can prepare to take advantage of machine learning capabilities. This narrative review aims to bring together information from the past to better articulate what may happen in the future regarding machine learning use in soccer, emphasizing injury risk assessment. Finally, we aim to provide practical tips for the health and performance staff in soccer clubs (i.e., physicians, physiotherapists, coaches, strength and conditioning staff, sports scientists) on how they can pave the way within the club and take competitive advantage of machine learning use. Accordingly, this manuscript is

TABLE 1. Summary of studies using machine learning approaches exclusively with soccer players as their studied population.

Study	Participants Period of study	Main outcome studied	Main finding	Topic
Ayala et al. [5]	96 male professional players, 1 season	Hamstring strain injuries predicted	The prediction model showed moderate to high accuracy	Injury risk/Injury occurrence prediction
Oliver et al. [18]	355 elite youth players aged 10–18 years old, 1 season	Injuries predicted	The best performing decision tree model provided a specificity of 74.2% and sensitivity of 55.6% with an AUC of 0.663	
Rossi et al. [17]	26 professional male players, 1 season	Non-contact injuries	Machine learning technique can detect around 80% of the injuries with about 50% precision, far better than the baselines and state-of-the-art injury risk estimation techniques	
Rommers et al. [7]	734 players, under-10 to under-15 age categories, 1 season	Non-contact injuries	Machine learning algorithm was able to identify the injured players in the hold-out test sample with 85% precision, 85% recall (sensitivity) and 85% accuracy	
Bongiovanni et al. [35]	16 male under-15 team players, 1 season	Sprint CoD, CMJ & aerobic fitness performance prediction	Anthropometric features were predictors of sprint performance and aerobic fitness, not CoD and CMJ	Physical performance prediction
Campbell et al. [29]	As the authors state “The data encompassed multiple seasons (2013–2018) and was pooled across pre-season and in-season training sessions” without including information on the data size.	Internal (sRPE) and external load (total distance covered)	Very low predictive ability	Players’ monitoring
Geurkink et al. [28]	46 elite male players, 61 training sessions, 913 observations	Predicted sRPE	sRPE was predicted accurately	
Jaspers et al. [27]	38 professional male players, 2 seasons	External and internal training load	More accurate predictions of training Rate of Perceived Exertion from external workload data in combination with pre-session wellness	
Op De Beéck et al. [26]	One soccer team (no information for duration of the study)	Future wellness items (i.e., fatigue, sleep quality, general muscle soreness, stress levels, and mood)	Wellness was predicted based on internal and external workload data. Their effect sizes indicate that the external load and internal load, separately and in combination, do not have sufficient predictive ability	

TABLE 1. Continue.

Study	Participants Period of study	Main outcome studied	Main finding	Topic
Perri et al. [36]	28 sub-elite players, 1 season	Wellness index as predicted by internal training load	Machine learning technique predicted the wellness index based on previous training day internal load	
Dick et al. [37]	Tracking data consisting of a sequence of coordinates of all players and the ball for a set of soccer games	Successful attacks	Proposed an approach to learn valuations of multiplayer positioning using positional data	Performance analysis
Goes et al. [23]	Position tracking data of 118 Dutch Eredivisie matches, containing 12424 attacks	Successful attacks	Identified dynamic formations based on position tracking data, and identified dynamic subgroups for every timeframe in a match	
Link and Hoernig [24]	Data from 60 matches in the German Bundesliga, 1 season	Models for detecting individual and team ball possession based on position data	Match event were detected automatically	
Montoliu et al. [25]	Football videos including two regular league matches played by up to four professional teams	Team activity recognition and analysis	The proposed method performed the team activity recognition task with high accuracy	
Wang [8]	Teams playing in UEFA EURO2012	Technical and tactical analysis of teams	Key performance indicators were identified	
Zago et al. [38]	13 elite female players performed a shuttle run test, wearing 6-axes inertial sensor at the pelvis level	Prediction of turn direction, speed (before/after turn) and the related positive/negative mechanical work	Good predictive ability of the machine learning algorithms	Movement analysis
Barron et al. [39]	966 outfield male players, 1 season	Identify key performance indicators that influence player's career status	Specific technical characteristics correctly predicted 78.8% of the players' league status with a test error of 8.3%	Player's career trajectory
Matesanz et al. [40]	Soccer players' transfer network among 21 European first leagues between the seasons 1996/1997 and 2015/2016	Table rank, UEFA points	Clubs with the highest transfer spending achieve better performance	Club performance
Sahin and Erol [41]	Data of 236 soccer games, 1 season	Predict the attendance demand in European soccer games	A model was proposed to predict attendance with higher accuracy	Match attendance

Note: AUC: Area Under the Curve; CoD: change of direction; CMJ: countermovement jump; sRPE: session rating of perceived exertion

targeting the applied sports scientists and sports medicine staff who have limited knowledge and interest in the technical and computing aspects of machine learning.

Machine learning evolution in soccer

Decision-makers (i.e., club's owners and top managers, directors of health and performance) and team support staff/practitioners constantly strive for accurate and time-efficient methods to predict performance and assess the injury risk (or even predict the occurrence of a musculoskeletal injury). Performance prediction can help develop better training programs and shape effective game strategies, whereas injury risk prediction can protect athletes' health and eventually optimize performance [9].

To achieve these goals, practitioners are using the latest technological advances (e.g., tracking systems such as GPS technology and inertial movement sensors, fatigue and wellness-related biological and psychological markers, screening tests) and the best analytical methods [10, 11, 12]. In the past, regression analysis has been used to assess injury risk [3] and predict sports performance. The problem with this traditional statistical analysis is that it eliminates the variables that are not linearly associated with the dependent variable. This will create a bias when searching for the interactions among variables [5, 6, 7]. The secondary problem is that traditional statistics cannot account for the effect of multiple factors on the dependent variable. For example, to assess the risk of sustaining a musculoskeletal injury, multivariate analysis models take into account the independent effect of factors in isolation, like previous injury or muscle strength, and the potential interactions between a limited number of factors (i.e., 2 to 3 each time). However, injury is a complex phenomenon [13]. Many parameters may account independently or in combination to its occurrence, including a previous injury, muscle strength imbalances, aerobic fitness or workload [14]. To account for the etiological factors' complexity, machine learning algorithms are now being used in high-performance sports for injury prediction [7].

Machine learning analysis usually involves two phases. In phase one, an algorithm is developed based on the actual data. In phase two, this algorithm is applied to another group or a sub-group of the initial sample to assess its performance [1]. A well-known tool to assess the models' performance is the area under the curve (AUC) for the receiver operating characteristics (ROC) curve. The ROC curve is created with a true positive rate on the vertical axis and the false positive rate on the horizontal axis. The true-positive rate is known as the sensitivity, and the false-positive rate is the probability of a false alarm and is calculated as 1-specificity. The higher the AUC, the better the prediction model [5, 6, 7].

Although there is some evidence [5], we are unsure if musculoskeletal injuries can be predicted through performance and screening tests to an accuracy suitable for valid decision making. As stated by Bahr [14], for a screening test to predict injuries, at least two things are needed: a strong relationship between the test outcome

and the injury risk and the need for the test to be examined in relevant populations using appropriate tools. Both criteria have not been met with currently available tests, and it is unlikely that due to the nature of injuries, we ever will have sufficiently accurate tests available [15]. We believe these approaches (i.e., screening tests) and the statistical procedures can help identify early signs of elevated injury risk for the team supporting staff and the players to act in advance. One of the contributions of machine learning may be that it can develop the cut-off values needed from the sample data.

Despite the criticisms, the assessment of injury risk is a hot topic in soccer, as injury occurrence and the associated absence from training and match play are related to lower team ranking and lower club earnings [16]. This might be a reason explaining the growing number of research on machine learning to predict injuries [3]. If not the first study on the topic, one of the first was that by Rossi *et al.* [17]. The authors collected GPS data that described 26 professional male players' workload over one season and constructed injury prediction models. The best machine learning algorithm could detect around 80% of the injuries with 50% precision and an AUC of 0.76. As the authors argued, the algorithm was "far better than the baseline and state-of-the-art injury risk estimation techniques" [17]. It should be mentioned at this point that risk estimation is not equal to risk prediction. People tend to think that predicting involves saying something will happen, whereas estimation is thought to involve how likely something is bound to happen. However, risk prediction is nothing more than calculating a probability.

Recent studies claim that injuries can be predicted by measurements taken in the pre-season. This is a challenging concept, and at least 3 studies were published in the last 2 years on the topic [5, 7, 18]. Traditionally, sports medicine and sports science staff test athletes in the pre-season for various attributes (e.g. body composition, cardiovascular fitness, muscle strength, flexibility, sprinting, and change of direction ability) to analyze the data and assess the injury risk at specific time points in the course of the season [5, 6, 7, 18]. The assumption is that any disadvantage diagnosed with these tests will result in an elevated risk of musculoskeletal injury. Machine learning algorithms have shown to predict injuries with moderate to high accuracy (Table 1). Despite that, we are unsure of what this "moderate to high accuracy" means in clinical terms.

Ayala *et al.* [5] screened 96 players regarding their history of injuries, psychological and neuromuscular risk factors as part of their pre-season assessment. The best model showed moderate to high accuracy with an AUC score of 0.83, a true positives rate of 77.8% and true negatives of 83.8% in predicting hamstring strain injuries. Similarly, Oliver *et al.* [18] performed neuromuscular testing in pre-season and followed 355 youth soccer players for the entire soccer season. The machine learning model showed a specificity of 74.2% and sensitivity of 55.6%, with an AUC of 0.66. Interestingly, logistic regression provided a specificity of 97.7% and a sensitivity of 15.2%, with an AUC curve of 0.66, suggesting a much higher sensitivity with machine learning in predicting injuries than traditional statistics [18].

However, it must be noted that an AUC of 0.66 is not acceptable for an injury prediction tool [18]. Rommers et al. [7] tested 734 young players for strength, flexibility, agility, and endurance in pre-season. Anthropometric data and occurring injuries were also recorded throughout the entire season. The machine learning algorithm predicted injury with a precision of 86% in the training data set [7].

In conclusion, it seems that machine learning techniques can assess the injury risk with moderate to high accuracy based on pre-season screening data. Despite that, we are still unsure what this “moderate to high accuracy” means in clinical terms. Furthermore, it should be mentioned that injury risk estimation is not equally interpreted as injury prediction. Even though fundamentally, in prediction models, one looks for the probability of an outcome, it is easily (and most frequently) wrongly interpreted as the estimation and outcome ‘will’ occur, instead of ‘can’ occur.

Challenges with regards to injury prediction

The problem with the approaches mentioned above is that data collected months before an injury cannot account for the dynamic nature of soccer activities and the changes that may happen to the players. Athletes are exposed to a specific workload that may modify the relation between a parameter and the injury risk [14]. Indeed, it is assumed that the accuracy with machine learning can be improved with data (e.g., workload, readiness, physiological and contextual data like training ground condition, shoe type) collected as close to the event (the injury occurrence) possible. Real-time data on athlete’s physiology (e.g., heart rate, body temperature), mechanical responses (e.g., fatigue-induced alterations in mechanics of movements), and other contextual factors (e.g., pitch condition, shoe-surface properties) could add value and improve the accuracy of machine learning techniques in the future. This will be one of the biggest challenges soon with integrating big data and machine learning applications in a way that adds a competitive advantage in sports.

There are at least two more problems associated with the use of machine learning in soccer injury prediction: 1) the low incidence of specific injuries that prevent algorithms from reaching a higher accuracy [19]; and 2) the uncertainty when applying machine learning algorithms to another setting or using slightly different data collection procedure than the original one. Regarding the first point, in elite soccer, one can expect about 50 injuries per team during a season, a very small number to create prediction models with high accuracy in a single team [19]. The situation becomes more challenging when considering the different types of injuries within a soccer squad. The problem of low cases in most studies is called the imbalanced data-sets problem in data science [5, 6, 7, 20], because one class (in this case, the injured athletes) is underrepresented in the data-set [20].

Machine learning models are usually biased towards the majority class (in this case, the non-injured athletes), which means the algorithms may inaccurately predict the minority class (the injury cases). Experts in the field have suggested technical solutions to this

problem, and the readers may find the technical details elsewhere [5, 6, 7, 20]. However, another potential solution is to collect data from many teams and treat them as one sample. As an example, all teams of a national league could send their data to a common database. Nevertheless, what works in one team may not work in another. As stated before, injury risk is context-specific and essential factors like the team, medical support, and staff communication are crucial elements [21]. Therefore, we need more data specific to the players. Then, we move to the second challenge, which is the uncertainty when applying a machine-learning algorithm to a different setting [5, 6, 7]. It seems that even a slight deviation in the procedure of data collection may affect the outcome. As suggested, if a new test is added or an existing one is executed differently from the original one used for the algorithm development, this could affect the algorithm performance [5, 6, 7].

What can soccer learn from other sports and scientific fields?

Besides injuries, the occurrence of illnesses is of major concern in sports due to potential loss of training and hence the risk of under-performance. An earlier study has developed predictive models for illnesses based on workload data in rugby league players, and this is an interesting dimension with high practical importance [22]. Thirty-two professional rugby league players were recruited, their internal training and match load were recorded, and perceptual well-being ratings were collected for 29 weeks during a rugby league season. A decision-tree model was developed with the risk factors contributing to the self-reported illness and their cut-off values [22]. Overall, a reduction in well-being combined with an increased internal training load were the main contributors to the self-reported illness occurrence. The area under the ROC curve ranged from 46% to 80%, depending on the model [22]. The ROC range may indicate that more work is needed for the machine learning algorithms to provide risk assessments with higher accuracy based on this nature of data.

Machine learning use in other outcome measures in soccer

In soccer, performance analysis is the topic with most studies related to machine learning published so far (Table 1). Most of these studies are related to the automatic detection of match events [23, 24, 25]. The development of algorithms based on machine learning, which will detect match events with higher accuracy faster, is advantageous for high-performance teams who analyze big data (e.g., data of their team and those of the opponents) [24].

An interesting dimension is applying machine learning for predicting a player’s wellness [26]. The authors used machine learning algorithms to predict wellness based on external and internal load data during training sessions. Wellness was calculated every morning from scores on perceived fatigue, sleep quality, general muscle soreness, stress levels, and mood state. Machine learning was applied to develop predictive models for the next day’s wellness score based on the last day’s training load (e.g., external and internal load) and wellness score. Although this is a promising dimension, the analysis

showed that the data did not have sufficient predictive ability for the next day's wellness score [26]. In the same topic, Jasper et al. [27] and Geurkink et al. [28] have employed machine learning to predict training session's ratings of perceived exertion (sRPE) from external workload data (i.e., GPS-derived). The analyses showed that sRPE could be predicted accurately for sRPE values below 8 [28]. This work is very relevant because coaches may design better training methods using past GPS-derived data to predict sRPE and hence the internal workload of the players with higher accuracy.

If wellness data have a predictive value for subsequent training, practitioners would inform coaches to modify training volume and intensity when necessary. This was the aim of a recent study conducted by Campbell et al. [29], who analysed a pool of data captured and stored in an athlete's management system platform. As the authors state, "the data encompassed multiple seasons (2013–2018) and was pooled across pre-season and in-season training sessions" without including information on the data size. This study showed the very low predictive ability of wellness data on internal (s-RPE) and external load (total distance covered) in soccer players [29].

Ethical and technological considerations with the use of machine learning

As with every new technology, there are some ethical considerations regarding the unintended use of machine learning [30]. It is tempting to use existing data that was not directly gathered for machine learning studies. Consent, as such, is not always given for the use of data by the athletes. Practitioners should carefully review the process and ensure their actions obey the law and follow the authorities and organizational policies. For instance, the use of databases containing personal information collected without the consent of the individual(s) is a major issue, and practitioners should stick to the rules. This is extremely important regarding the use of medical records that contain sensitive personal data [31]. Therefore, data protection experts' contribution and approval are highly recommended when using machine learning in soccer.

Another consideration is the use of machine learning for decision-making. This brings management and leadership aspects to the front stage of successful management of risk using machine learning [32]. For instance, how does the supporting team staff deal with false-positive cases communicated to the coach or the true-positives not communicated? What is the acceptable threshold for the identified high-risk cases to be communicated to the coaches and the top management? Education of everyone involved with data analysis and decision-making is therefore of utmost importance [33].

In the future, the predictive models could integrate data related both to intrinsic factors (i.e. demographics, anatomical, physiological, psychological profile) and extrinsic factors (i.e. workload and environmental data). The addition of veracity metrics related to physical testing and workload monitoring could also help. A recent paper reported that data veracity (accuracy, reliability, and quality of data) was found for 54% of tools and 23% of the parameters used in testing and workload monitoring in soccer studies [34].

CONCLUSIONS

In this narrative review paper, we have attempted to shed some light on the use of machine learning in soccer, emphasizing injuries, given practitioners' interest on this topic. Machine learning does not seem to have high predictive ability in every setting. It seems that machine learning can help to identify early signs of elevated risk for a musculoskeletal injury. Future research should account for musculoskeletal injuries' dynamic nature for machine learning to provide more meaningful results. Performance analysis is the area with most research at the moment. Knowledge in this area is growing and is having practical applications in the club setting.

Conflict of interest

The authors declare that they have no competing interests.

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Substitute running outputs in elite youth male soccer players: less peak but greater relative running outputs

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ABSTRACT: Coaches consider substitute players to be a substantial factor in influencing the outcome of a soccer match. Substitute players are expected to make physical impact on the match by superseding the running output of the player they replaced and are a key tool for managing in-game fatigue and influencing the outcome of a game. This study investigated the physical impact and internal response of substitute players, compared to starting and full-match players. We also sought to determine if differences between substitution statuses were influenced by playing position. Players wore 15-Hz global positioning system tracking devices across 29 competition matches and were categorised according to their substitution status (full-match, starters, substitutes) and playing position (external defender, midfield, external attacker and central attacker). Peak total (TD) and high-speed running (> 5.0 m/s) distance (HSRD) were calculated using 1-, 2- and 5-minute rolling epochs. Relative running demands were reported as TD and HSRD per minute of total playing time. Substitute players performed less peak TD and HSRD in 1-, 2- and 5-minute epochs, and reported lower RPE compared to starting and full-match players. In contrast, substitutes performed greater relative HSRD per minute than starting and full-match players ($p < 0.001$, $|d|$ range = 0.35–1.34). In conclusion, substitute players may have a relative physical impact but do not replicate or supersede the peak demands of full-match players. Coaches and practitioners should implement targeted warm-up interventions to enhance substitute readiness to meet the peak running demands in order to have a more effective physical impact.

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INTRODUCTION

During regulation soccer matches, coaches from each team are permitted to replace up to three on-field players from a group of 6–7 reserve players. Once a player has been substituted, they may not return to the field of play. Prior studies have demonstrated that players' total and high-speed running distance per minute progressively declined over the course of match-play due to fatigue [1–4]. The tactical use of substitutions is a key mechanism for coaches to counteract the effects of game-induced fatigue to avoid decreases in individual and team performance [3–5]. The physical impact of substitutes can be deemed effective when the substitute players physical work rate supersedes the player being replaced [4–6]. There is often an assumption by coaches that substitutes have a positive physical impact on a match [5], however, studies detailing the running demands of elite youth soccer players commonly omit match contributions by substitutes [2, 7–10], and therefore the empirical evidence for this assumption is limited.

Research detailing match contributions from full-match, starting and substitute players in elite senior male soccer demonstrated that substitutes performed more relative total distance per minute and high-speed running (5.0–6.95 m/s) distance per minute compared to players who started or completed the match [3, 11]. However, previous investigations have also highlighted key differences in the running demands between elite senior and youth male soccer players [12]. For example, elite youth male soccer players have been found to cover greater total distances than elite senior players during match-play, although this was primarily attributed to larger distances covered at low-intensity (< 3.33 m/s) [12]. Alternatively, elite senior male soccer players have demonstrated more distance covered at high-speed (> 6.94 m/s) compared to their youth counterparts, likely attributed to their greater physical capabilities [12]. The results from these studies suggest that data pertaining to the influences of contextual factors such as substitution status in elite senior male

soccer players cannot be inferred and used to understand the physical demands of match-play in elite youth male soccer players.

The physical demands of soccer match-play are typically reported as absolute (e.g., total distance covered in a match) and relative (e.g., average distance covered per minute of match time) values to highlight both the total external load and average intensity of players [9, 10, 12]. However, several investigations have demonstrated that utilising absolute and relative metrics may underestimate the most intense periods of match play faced by players [8, 13–15]. As such, the use of methodologies to identify the peak running demands of match-play (such as fixed [e.g., 0–5 min, 5–10 min, 10–15 min] and rolling [e.g., 0–5 min, 1–6 min, 2–7 min] epochs [i.e., time intervals]) have become increasingly common, with the intent to better understand the physical requirements of players [8, 13–15].

Practically, provided that players are adequately prepared for pitch entry, coaches should be able to make tactical player replacements with the aim that substitute players are able to attain similar or greater running outputs as starting and full-match players [5, 16–18]. The use of Global Positioning Systems (GPS) has facilitated the quantification of peak and relative running demands and further aided in the understanding of the external loads of match-play [9, 13–15]. However, given that substitute players experience reduced match-time compared to those who complete an entire match or are in the starting line-up, it is also important to assess how players respond to such external loads [19–21]. Measurements such as rate of perceived exertion (RPE) are commonly implemented to assess associated players internal response [19–22]. However, there is a lack of studies that have analysed the internal response to the peak and relative running demands of substitute players. Therefore, the aim of this study was to analyse the physical impact and internal response of substitute players, compared to starting and full-match players. This study also sought to determine if the differences between substitution statuses were influenced by playing position.

MATERIALS AND METHODS

Experimental approach to the problem

This study implemented a longitudinal observational study design. Data were collected on twenty-one (21) elite youth male soccer players during national (National Youth League, $n = 8$) and state (National Premier League, $n = 21$) competitive soccer matches ($n = 29$) across a 13-month period. National Premier League (NPL) competition matches are classified as semi-professional fixtures and were played throughout an eight-month competition calendar period (March – October). National Youth League (NYL) competition matches are classified as youth professional development fixtures and were played across a three-month competition calendar period (November – January). The running demands for each player during match-play were captured using a global positioning system (GPS). A rate of perceived exertion (RPE) was collected within 30-minutes of

a player completing their match involvement to assess subjective match intensity. Players were categorised according to their substitution status and playing position in each match.

Participants

Twenty-one ($n = 21$) outfield elite youth male soccer players (age: 15.6 ± 0.7 yrs.; height 173.1 ± 5.2 cm; body mass 64.9 ± 6.2 kg; Yo-Yo Intermittent Running Test (Level 2) score: 771 ± 220 m) from an Australian Under-17 National Centre of Excellence squad were monitored during 29 competition matches. A typical training week consisted of 4–5 soccer specific on-field sessions, 1–2 gym-based strength and conditioning sessions, 1–2 competition matches per week and 1–2 post-match contrast water immersion recovery sessions. All players and parents or guardians were informed of the risks and benefits of participation in this study prior to providing informed written consent. This study was approved by the Human Research Ethics Committee of the University of Canberra, Australia (Project Number: 16-195).

Procedures

Each player competed in an average of 14 matches (range = 3–27), with a total of 300 individual match files used for analysis. Out of the 300 observations, 75 were for substitutes (players who replaced the starting players at some stage of the match), 76 were for starters (players who started the match and were replaced by a substitute player) and 149 were for full-match players (players who played the full 90-minutes of the match). Players were also categorised according to their position in each match and were categorised as: Central Attackers (CA, $n = 33$ observations), External Defenders (ED, $n = 83$ observations), Midfielders (MD, $n = 105$ observations) and External Attackers (EA, $n = 79$ observations). To account for participants featuring in different playing positions and substitution statuses across different matches, these were defined for each individual match accordingly. Central Defenders were not substituted during the data collection period and were therefore omitted from the analysis ($n = 58$ observations). Furthermore, players who were substituted in the last 5-minutes of match-play were omitted to minimise the effect of tactical substitutions made to delay match-play ($n = 3$ observations).

A 4-3-3 formation was used in all observed matches throughout the data collection period. Matches were preceded by a 30-minute standardised warm-up consisting of small-sided games, short and intermediate length maximal sprint efforts, short and long passing, shooting, and dynamic stretching. The field dimensions for matches were 100×60 m. Each match was 90-minutes in duration, separated into two 45-minute halves with any additional time determined by the referee. All matches were played under the same competition rules, limiting each team to three substitutions and a 15-minute break for half time. Competition match times and environmental conditions varied throughout the data collection period in accordance with NPL and NYL seasonal fixtures.

Data collection

The physical demands of players during matches were captured using commercial 15 Hz GPS tracking devices (SPI HPU, GPSports, Canberra, Australia) according to manufacturer instructions. To minimise the effect of inter-unit error, each player was allocated the same GPS device for the duration of the data collection period. The inter-unit reliability for the GPS devices (expressed as a coefficient of variation) has been reported as 1.4% for total distance, 7.8% for distance at speeds between 2.0 m/s to 5.9 m/s, and 4.8% for distance covered at speeds > 5.9 m/s [23]. Each device was turned on 30-minutes before each match to ensure satellite connectivity, and between 4 to 12 satellites were available for connectivity and signal transmission during match-play, satisfying the criteria for ideal positional detection [24]. Horizontal dilution of precision (HDOP) was not reported by the proprietary software (Team AMS, Canberra, Australia). Raw GPS data files were extracted using proprietary software (Team AMS, Canberra, Australia) after the completion of each match. Data was trimmed so that only on-field playing time was included in the analysis.

Recorded GPS data included total distance covered (TD), and high-speed running distance (HSRD), defined as distance covered at speeds > 5.0 m/s. This threshold was similar to those used in previous investigations [7, 11]. To calculate relative running outputs, the absolute values of TD and HSRD were divided by the duration (in minutes) of the match the player was involved in. To calculate peak TD and HSRD, 1-, 2- and 5-minute rolling epochs were employed as fixed epochs have been demonstrated to underestimated total (7–10%) and high-speed (12–25%) distance (defined as > 5.5 m/s) in elite senior male soccer players [14]. Each match file was split into 30-second time intervals and 1-, 2-, and 5-minute rolling sums were then calculated. The peak TD and HSRD were then defined as the maximum TD and HSRD achieved in a 1-, 2- and 5-minute epoch. An example of this process is shown in Table 1. To allow for comparison between the different epoch lengths, peak TD and HSRD for 2- and 5-minute rolling epochs were expressed as relative per minute values, calculated by dividing the maximum distance achieved by the duration of the 2- and 5-minute epoch.

A rate of perceived exertion (RPE) was collected using a CR-10 scale to assess subjective match intensity [19–22]. The RPE was collected within 30-minutes of match completion, or within 30-minutes of a player coming off the field if they were substituted. For example, if a player was substituted during the 70th minute of a match, that player completed the RPE CR-10 scale within the next 30-minutes. This method has been previously implemented to quantify subjective match intensity and is a valid monitoring tool in elite youth soccer [19–21].

Statistical analysis

Statistical analyses were conducted using R version 4.0.3 [25] and RStudio version 1.4.1103 [26]. A Linear Mixed Model (LMM) was developed using the *lmer* function from the *lme4* package [27] to

TABLE 1. Example of 1-, 2- and 5-minute rolling epoch calculations

30 second Time Splits	Distance	1-minute	2-minute	5-minute
0–30 sec	44			
30–60 sec	81	125		
60–90 sec	62	143		
90–120 sec	103	165	290	
120–150 sec	56	159	302	
150–180 sec	77	133	298	
180–210 sec	70	147	306	
210–240 sec	67	137	270	
240–270 sec	54	121	268	
270–300 sec	60	114	251	674
300–330 sec	57	117	238	687
330–360 sec	49	106	220	655
360–390 sec	88	137	254	681
390–420 sec	61	149	255	639
420–450 sec	64	125	262	647
450–480 sec	107	171	320	677
480–510 sec	91	198*	323*	698
510–540 sec	58	149	320	689
540–570 sec	64	122	320	699
570–600 sec	91	155	304	730*

* Denotes maximum distance achieved in 1-, 2- or 5-minute rolling epoch. Peak distance is calculated as the maximum distance achieved in a 1-, 2- and 5-minute epoch. For example, the maximum distance achieved for a 1-minute rolling epoch is from the 450–510 sec window. The maximum distance achieved for a 2-minute rolling epoch is from the 390–510 sec window and the maximum distance achieved for a 5-minute rolling epoch is from the 300–600 sec window. To allow for comparison between the different epoch lengths for peak TD and HSRD, 2- and 5-minute rolling epochs were expressed in relative per minute values, calculated by dividing the maximum distance achieved by the duration of the 2- and 5-minute epoch.

determine the difference in peak TD and HSRD (dependent variables) between substitution status and positions (fixed factors) for each epoch length. In addition, separate LMM's were conducted to determine the difference in relative TD and HSRD (dependent variables) between substitution status and positions (fixed factors). A LMM was also performed to analyse the difference in RPE (dependent variable) for substitution status and positions (fixed factors). For each LMM, the repeated measures for each player were treated as a random factor. A Type II Wald F test was conducted using the *Anova* function from the *car* package [28] to determine the significance (alpha level = 0.05) of any interaction or main effects between substitution status and playing position. The assumptions of homoscedasticity

and linearity were confirmed upon visual inspection of plots of the fitted values against the residuals [29]. The assumption of normality was determined upon visual inspection of histograms and Q-Q plots of the residuals. Effects size statistics were calculated by Cohen's d , using the least squares means and the pooled standard deviation of the random effects to account for the structure of the LMM [30]. The effect sizes were interpreted as trivial: $|d| < 0.2$, small: $|d| = 0.2$ – 0.49 , moderate: $|d| = 0.5$ – 0.79 and large: $|d| \geq 0.8$ [31]. Least-squares means and 95% confidence intervals were calculated using the *ls_means* function from the *lmerTest* package [27].

RESULTS

No interactions were identified between substitution status and playing position for peak TD across 1- ($p = 0.863$), 2- ($p = 0.924$) and 5-min ($p = 0.645$) rolling epochs and relative TD calculations ($p = 0.283$). Main effects were identified for substitution status for peak TD in 1- ($p = 0.003$), 2- ($p = 0.004$) and 5-min ($p < 0.001$) rolling epochs and relative TD calculations ($p < 0.001$). Figure 1 demonstrates that in 1- and 2-minute rolling epochs central attacker substitute players recorded less peak TD compared to full-match players. Similar results were found for external defenders and midfielders in 1-, 2- and 5-minute rolling epochs with substitute players reporting less peak TD compared to starting and full-match players. External attacker substitute players demonstrated lower peak TD compared to starting and full-match players in 1-, 2- and 5-minute rolling epochs.

Substitute players reported greater relative TD in comparison to full-match players for central attackers (Figure 3). Similar results were found for midfielders and external attackers with substitute players reporting greater relative TD running outputs in comparison to starting and full-match players (Figure 3).

No interactions were observed between substitution status and playing position for peak HSRD across 1- ($p = 0.507$), 2- ($p = 0.591$) and 5-min ($p = 0.861$) rolling epochs and relative HSRD calculations ($p = 0.414$). Main effects were also identified for substitution status for peak HSRD in 1- ($p < 0.001$) and 2- ($p = 0.017$) rolling epochs as well as relative HSRD calculations ($p < 0.001$). No main effects were identified for substitution status in 5-minute ($p = 0.070$) rolling epochs. Substitute players perform less peak HSRD in 1-minute rolling epochs compared to starting and full-match players in central attacker, external defender, and external attacker positions (Figure 2). Substitutes are reported to produce less peak HSRD compared to starting and full-match players in 2- and 5-minute rolling epochs for central attackers and external attackers.

Within-positional differences for central attackers demonstrated that substitute players reported greater relative HSRD in comparison to full-match players (Figure 4). External defenders, midfielders and external attackers also displayed similar within-positional differences with substitute players reporting greater relative HSRD than starting and full-match players (Figure 4).

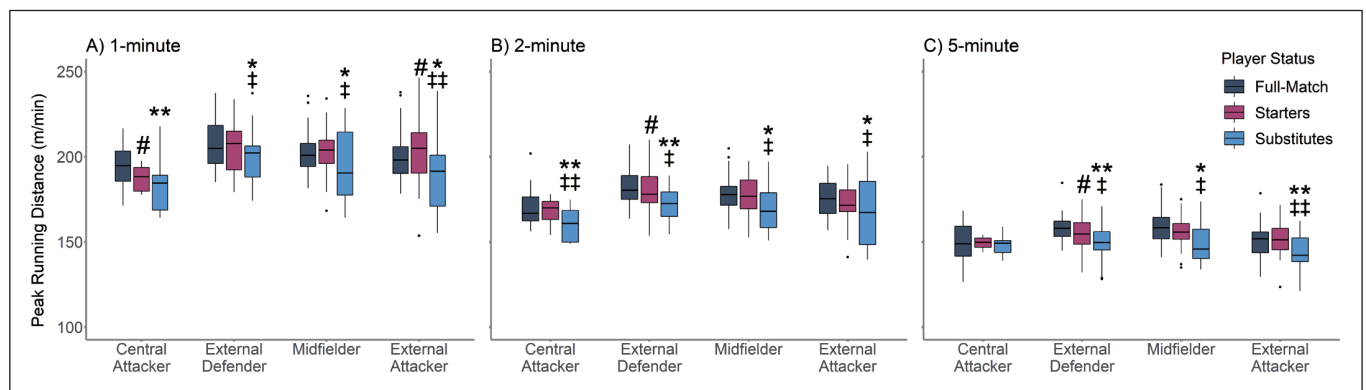


FIG. 1. Peak Total Distance (TD) Characteristics According to Substitution Status and Position for (A) 1-, (B) 2- and (C) 5-minute rolling epoch lengths

* $|d|$ 0.2–0.49 small effect size between Substitutes to Full-match players.

** $|d|$ 0.5–0.79 medium effect size between Substitutes to Full-match players.

*** $|d| \geq 0.8$ large effect size between Substitutes to Full-match players.

$|d|$ 0.2–0.49 small effect size between Starting and Full-match players.

$|d|$ 0.5–0.79 medium effect size between Starting and Full-match players.

$|d| \geq 0.8$ large effect size between Starting and Full-match players.

‡ $|d|$ 0.2–0.49 small effect size between Substitute and Starting Players.

†† $|d|$ 0.5–0.79 medium effect size between Substitute and Starting Players.

††† $|d| \geq 0.8$ large effect size between Substitute and Starting Players.

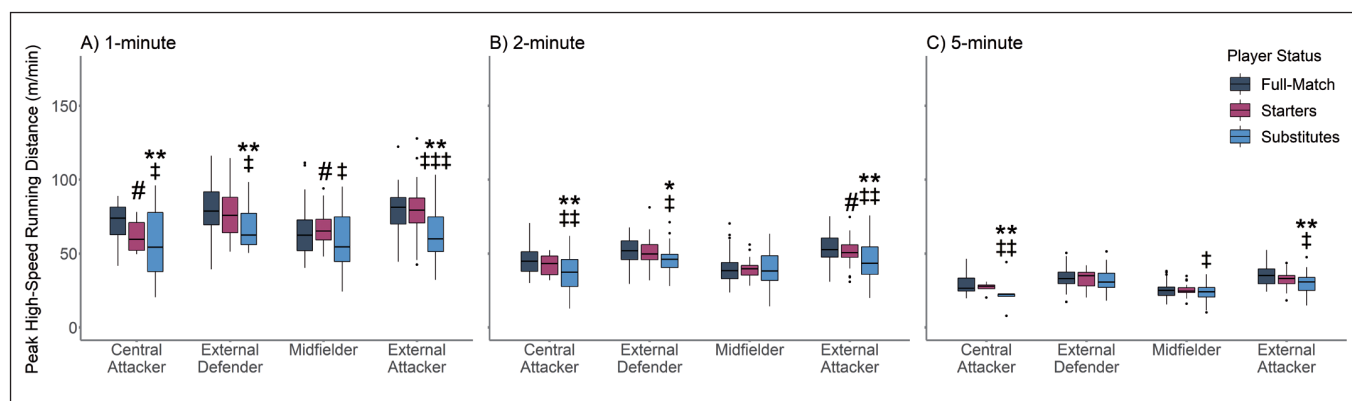


FIG. 2. Relative High-Speed Running Distance (HSRD) Characteristics According to Substitution Status and Position for (A) 1-, (B) 2- and (C) 5-minute rolling epoch lengths

* $|d|$ 0.2–0.49 small effect size between Substitutes to Full-match players.
 ** $|d|$ 0.5–0.79 medium effect size between Substitutes to Full-match players.
 *** $|d| \geq 0.8$ large effect size between Substitutes to Full-match players.
 # $|d|$ 0.2–0.49 small effect size between Starting and Full-match players.
 ## $|d|$ 0.5–0.79 medium effect size between Starting and Full-match players.
 ### $|d| \geq 0.8$ large effect size between Starting and Full-match players.
 ‡ $|d|$ 0.2–0.49 small effect size between Substitute and Starting Players.
 †† $|d|$ 0.5–0.79 medium effect size between Substitute and Starting Players.
 ††† $|d| \geq 0.8$ large effect size between Substitute and Starting Players.

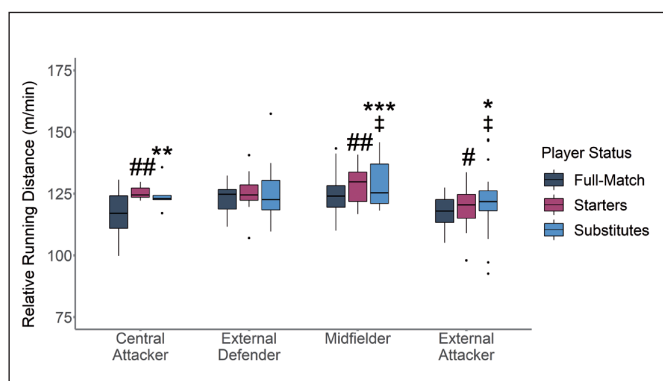


FIG. 3. Relative Total Distance (TD) According to Substitution Status and Position

* $|d|$ 0.2–0.49 small effect size between Substitutes to Full-match players.
 ** $|d|$ 0.5–0.79 medium effect size between Substitutes to Full-match players.
 *** $|d| \geq 0.8$ large effect size between Substitutes to Full-match players.
 # $|d|$ 0.2–0.49 small effect size between Starting and Full-match players.
 ## $|d|$ 0.5–0.79 medium effect size between Starting and Full-match players.
 ### $|d| \geq 0.8$ large effect size between Starting and Full-match players.
 ‡ $|d|$ 0.2–0.49 small effect size between Substitute and Starting Players.
 †† $|d|$ 0.5–0.79 medium effect size between Substitute and Starting Players.
 ††† $|d| \geq 0.8$ large effect size between Substitute and Starting Players.

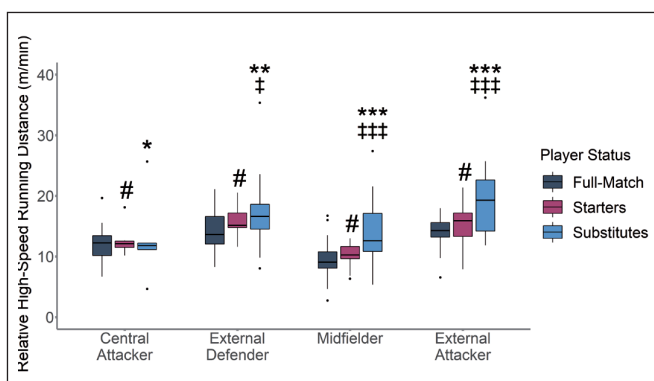


FIG. 4. Relative High-Speed Running Distance (HSRD) According to Substitution Status and Position

* $|d|$ 0.2–0.49 small effect size between Substitutes to Full-match players.
 ** $|d|$ 0.5–0.79 medium effect size between Substitutes to Full-match players.
 *** $|d| \geq 0.8$ large effect size between Substitutes to Full-match players.
 # $|d|$ 0.2–0.49 small effect size between Starting and Full-match players.
 ## $|d|$ 0.5–0.79 medium effect size between Starting and Full-match players.
 ### $|d| \geq 0.8$ large effect size between Starting and Full-match players.
 ‡ $|d|$ 0.2–0.49 small effect size between Substitute and Starting Players.
 †† $|d|$ 0.5–0.79 medium effect size between Substitute and Starting Players.
 ††† $|d| \geq 0.8$ large effect size between Substitute and Starting Players.

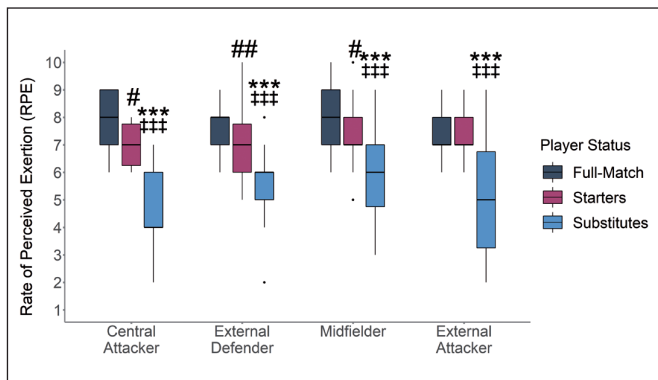


FIG. 5. Reported Rate of Perceived Exertion (RPE) according to Substitution Status and Position

* $|d|$ 0.2–0.49 small effect size between Substitutes to Full-match players.

** $|d|$ 0.5–0.79 medium effect size between Substitutes to Full-match players.

*** $|d| \geq 0.8$ large effect size between Substitutes to Full-match players.

$|d|$ 0.2–0.49 small effect size between Starting and Full-match players.

$|d|$ 0.5–0.79 medium effect size between Starting and Full-match players.

$|d| \geq 0.8$ large effect size between Starting and Full-match players.

‡ $|d|$ 0.2–0.49 small effect size between Substitute and Starting Players.

‡‡ $|d|$ 0.5–0.79 medium effect size between Substitute and Starting Players.

‡‡‡ $|d| \geq 0.8$ large effect size between Substitute and Starting Players.

No interactions were found between substitution status and playing position for RPE ($p = 0.246$). However, main effects were identified for substitution status ($p < 0.001$). Within-positional differences demonstrated that full-match players reported greater RPE scores than starting and substitute players for central attackers (Figure 5). Similar results were found for external defenders, midfielders and external attackers with full-match players reporting greater RPE scores than substitute players (Figure 5).

DISCUSSION

This study investigated the physical impact and internal response of substitute players, compared to starting and full-match players. This study also determined if differences between substitution statuses were influenced by playing position. The results of this study demonstrate that, when analysed using peak metrics, substitute players generally produced lower peak total distance and peak high-speed running distance compared to starting and full-match players (Figures 1 and 2). In contrast, when analysed using relative metrics, substitute players across all playing positions recorded greater relative

high-speed running distance compared to full-match players (Figure 4). Furthermore, the findings of this study report that starting and full-match players also recorded higher RPE compared to substitute players across all playing positions (Figure 5).

A substitute player's ability to 'come on and increase the speed of the game' or 'replace fatigued or underperforming players' by superseding the physical demands of the player being replaced is perceived by coaches and practitioners to be a significant factor in determining the outcome of a soccer match [5, 6]. However, the results from the present study showed that substitute players did not supersede the peak running output of starting and full-match players. These results could be partly explained by pre-entry warm up strategies. For example, Hills *et al.* [18] observed that typical match-day substitute warm up protocols failed to maintain core body temperatures of substitute players prior to pitch entry and subsequently impacted physical performance at the time of pitch entry. However, half-time re-warm up interventions have been cited to maintain sprint performance in the first 15-minutes of match-play compared to typical match-day half-time periods [16]. Consequently, the reduced peak high-speed running demonstrated by substitutes could be attributed to lack of physical preparation prior to pitch entry to meet the peak demands of match-play. However, further research is warranted to determine if specific warm-up interventions adequately prepare substitute players to meet the most demanding scenarios of match-play. Specifically, the differences of intermittent warm-up activities through the first half, half-time and second half of match play versus timed pre-entry interventions. For example, it is common practice for coaches to have numerous planned substitute scenarios according to possible score-line situations, i.e., losing 2-1 with 20-minutes remaining or winning 3-0 with 35-minutes remaining. Such pre-planned substitutions may be more effectively prepared for pitch entry using targeted interventions 30-minutes prior to pitch entry as opposed to intermittent warm-up activities. Interventions to prepare substitute players for preconceived tactical scenarios should be considered for future investigations.

Despite recording less peak high-speed running, substitute central attackers, external defenders, midfielders and external attackers displayed greater relative high-speed running compared to their full-match counterparts (Figure 4). Substitutes are typically introduced in the second half, recording a 15% increase in relative high-intensity (> 4 m/s) running when introduced at half-time and a 25% increase when introduced at the 75th minute of match-play compared to full-match players at the same time period [1,4,32]. Previous research has identified that player pacing behaviour may alter according to the knowledge of exercise duration [33]. For example, Ferraz *et al.* [33] demonstrated that short exercise durations elicit more aggressive pacing strategies in small-sided soccer games. As such, substitute players pacing strategies may differ to starting and full-match players in accordance with full knowledge of their density of time to perform and therefore reduced time to achieve an objective i.e., being substituted in the 75th minute to win the game in the remaining

time available [33]. Our results suggest that a substitutes knowledge pertaining to the density of time to make a physical impact promotes a more aggressive pacing behaviour, reflected in the increased relative high-speed running (Figure 4). Practically, this means that substitute players may employ aggressive pacing strategies to make a physical impact but fail to produce the same or greater peak running outputs as starting and full-match players [5, 6, 33]. A player's ability to perform actions at high-speed are critical in defensive and offensive situations such as pressing an opposition player for the ball or beating a defender in goal scoring situations [34, 35]. Considering the majority of goals are scored in the last 15-minutes of match-play [36] and are preceded by high-intensity running actions [34, 35], the inability to replicate or supersede the peak high-speed running of starting and full-match players indicates that substitutes may not be prepared for the most demanding, critical match situations, and may fail to provide a physical impact and subsequently influence the outcome of a match.

Substitute players recorded lower perceived match-intensity (RPE) compared to starting and full-match players in all positions (Figure 5). Research by Haddad et al. [22] suggested that session duration partially influences session RPE scores, accounting for 3.2% variance, and time spent at high intensity (i.e., between 91 and 100% of HRmax) accounting for 22.1% of variance in RPE scores. The reduced RPE scores recorded by substitute players may therefore be reflective of the reduced peak high-speed running indicating that substitute players spend less time in high-intensity zones during match-play. However, the total match duration is likely the main contributor to how elite youth soccer players internally respond to external demands and report subjective exertion [37]. Differential ratings of perceived exertion such as local-muscular (sRPEmus) and central-respiratory (sRPEres) have been used to enhance understanding and contextualise how players respond to external loads in elite soccer [37]. For example, Los Arcos et al. [37] found that players who completed greater than 70-minutes of match-play, i.e., starting and full-match players, reported higher average sRPEmus of 7.4 compared to sRPEres of 6.4. Alternatively, players that completed less than 20-minutes of match-play, i.e., substitutes, reported sRPEmus scores of 3.3 and sRPEres scores of 4.4 [37]. The results of this study are in alignment with Los Arcos et al. [37] suggesting that starting and full-match players have a greater subjective perception of muscular strain when reporting RPE compared to substitute players who likely report RPE based on central respiratory exertion.

Practically, employing interventions to ensure players are adequately prepared for 'substitute specific' scenarios may aid substitute players in replicating or superseding the peak running demands

of the player they replaced. In turn, this may ensure that substitute players are ready to perform in crucial situations and gain an advantage over the opposition. Furthermore, the data presented in this study does offer some evidence for coaches and practitioners when designing training benchmarks and post-match top-up conditioning sessions. For example, when implementing running drills to compensate for the lack of external load exposure post-game, the implementation of additional running drills with the intent to benchmark against the greatest peak running demands may aid in maintaining physical conditioning. This could be particularly important for players who are regularly omitted from the starting line ups, i.e., substitutes.

However, caution must be implemented when interpreting these findings and several limitations should be considered. Firstly, further investigation is required as the peak running output of substitute players is likely influenced by technical and tactical factors such as ball-possession metrics and opposition playing formations which are not accounted for in this study. Furthermore, future studies should seek to incorporate variables such as game status (i.e., win, draw, loss), score line at time of substitute entry, the number of substitutes utilised by each team as well as the location of the match (i.e., home versus away) and opposition team quality (i.e., team rankings). In addition, examining player training loads, RPE scores and wellbeing during the days preceding competition may further elucidate the subsequent impact of player fatigue and readiness on match running performance according to substitution status. Finally, regard should be given to the potential variance of results attributed to factors such as variation in match timing, environmental differences between matches and any extensive travel requirements.

CONCLUSIONS

In conclusion, the main finding of this study is that substitute players perform more relative high-speed running, but less peak total and high-speed running, compared to starting and full-match players. The results of this study suggest that a substitutes knowledge pertaining to the reduced time to make a physical impact may cause substitutes to modulate their efforts, resulting in an increased pacing strategy compared to starting and full-match players. Despite this substitute players failed to replicate or supersede the peak running demands of starting and full-match players, which could partly be explained by pre-entry warm up strategies.

Conflict of interest declaration

The authors declare no conflict of interest.

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Machine learning application in soccer: a systematic review

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ABSTRACT: Due to the chaotic nature of soccer, the predictive statistical models have become in a current challenge to decision-making based on scientific evidence. The aim of the present study was to systematically identify original studies that applied machine learning (ML) to soccer data, highlighting current possibilities in ML and future applications. A systematic review of PubMed, SPORTDiscus, and FECYT (Web of Sciences, CCC, DIIDW, KJD, MEDLINE, RSCI, and SCIELO) was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. From the 145 studies initially identified, 32 were fully reviewed, and their outcome measures were extracted and analyzed. In summary, all articles were clustered into three groups: injury ($n = 7$); performance ($n = 21$), which was classified in match/league outcomes forecasting, physical/physiological forecasting, and technical/tactical forecasting; and the last group was about talent forecasting ($n = 5$). The development of technology, and subsequently the large amount of data available, has become ML in an important strategy to help team staff members in decision-making predicting dose-response relationship reducing the chaotic nature of this team sport. However, since ML models depend upon the amount of dataset, further studies should analyze the amount of data input needed make to a relevant predictive attempt which makes accurate predicting available.

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INTRODUCTION

Machine learning (ML) is the science that allows computers to act as humans and learn, improving their knowledge from data feed over time in an autonomous way in any area of life [1]; where sport is not an exception [2–4]. The use of ML allows coaches to continually gain new knowledge, continuously adding data which leads to a constant solution update. Therefore, as long as the most appropriate and constantly changing data sources are used, the sport scientist may predict the future indicating some pieces of advice. These highlights may provide information about training design to minimize the occurrence of injuries [4], inducing both players' and teams' performance improvements [5–7], and even predicting athletes with the most potential [8–10]. In fact, ML becomes more relevant in soccer due to its chaotic nature and the unpredictability of players' behavior [11].

However, the use of a variety of algorithms that interactively learn from information becomes ML in a complex process in which the fundamental use of these algorithms allows the provision of more accurate data as long as new data is used [12, 13]. In brief, the algorithms used in ML are divided into (i) supervised learning (i.e., classification and regression) based on input/output data, and (ii) unsupervised learning (clustering) based on input data [14]. Some of the most considered ML predictor models are decision trees classifiers [3, 7], random forest [5, 7], and support vector machines [15, 16]. However, a wide range of other methods are being considered in soccer for injury, performance, and talent identification predictions [17, 18].

In practice, if data management is the main basis for producing the greatest levers in soccer, the use of predictive models has become the main challenge in the current era of big data. In

this scenario, these models depend upon the quality and amount of dataset composed by attributes, also named as features or variables, which are the items of data that are used in ML. The new possibility to record and store data has allowed a deep training of learning models, being able to predict what will happen with a high degree of accuracy. For example, López-Valencia *et al.* [3] and Ayala *et al.* [2], through personal, psychological, and neuromuscular risk factors compared four different algorithms that were capable to predict the majority of injury incidences. This predicting may become crucial due to the high degree of economic loss that clubs experience when a player is injured [19]. However, this is not the only way to apply ML in soccer. Other authors have analyzed the use of different variables such as tactical, technical, psychological, and contextual variables to predict players' and teams' future performance [17, 20–22], or even to choose the players with the most potential [8–10].

So, due to the exponential increments that have arisen since the first ML models in soccer [23], the summarization and extraction of a set of conclusions remains crucial in order to identify and consider when to make decisions. To date, the publication of some narrative reviews has summarized the use of different predictive techniques in team sports (basketball, baseball, football, cricket, and soccer) [24] and the recent advances in the use of ML and statistical methods for the prediction of maximal oxygen uptake [25]. Beyond, to the best of authors knowledge, just two systematic reviews have summarized the use of ML. Cludino *et al.* [14] summarized the use of ML in general team sports (basketball, American football, Australian football, volleyball, soccer, and handball) for injury risk and performance analysis; while Herold *et al.* [11] focused their systematic review on the current applications and future directions of predicting models applied to the attacking game phase. However, no study has summarized the application of ML in soccer for all injury prevention, performance prediction, and talent identification. Therefore, the aim of the

present study was to systematically identify original studies that applied ML with soccer data, highlighting current possibilities in ML and future applications. The present study may help team staff members in decision-making to predict dose-response relationships in order to reduce the chaotic nature of this team sport.

MATERIALS AND METHODS

This systematic review was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [26–28] and guidelines for performing systematic reviews in sport sciences [29].

Information sources

PubMed, SPORTDiscus, and FECYT (i.e., Web of Sciences, CCC, DIIDW, KJD, MEDLINE, RSCI, and SCIELO), were searched for relevant publications prior to February 19, 2021.

Search strategy

Keywords and synonyms were entered in various combinations in the title, abstract or keywords:

(soccer OR football) AND (“deep learning” OR “machine learning”)

Additionally, the reference lists of the studies retrieved were manually searched to identify potentially eligible studies not captured by the electronic searches. Finally, an external expert was contacted in order to verify the final list of references included in this scoping review in order to understand if there was any study that had not been detected through our research. Possible errata were searched for each included study.

Eligibility criteria

The inclusion and exclusion criteria can be found in Table 1.

To locate potentially relevant studies, the screening of the title, abstract and reference list of each study was independently performed

TABLE 1. Inclusion/exclusion criteria of selected studies.

Item	Inclusion Criteria	Exclusion Criteria
Population	Studies developed with soccer players	Studies developed with players from other team sports (basketball, rugby, Australian football, American football, futsal, etc.) or sport, even with videogames (i.e., FIFA computer games).
Intervention	The data was processed using machine-learning algorithms.	The data was not processed or not was processed using machine-learning methods.
Comparator	–	–
Outcome	Predictions were made about injury risk/prevention, performance, and/or talent identification.	Predictions about other issues (e.g., financial issues, social issues).
Study Design	The data were extracted during training sessions or matches.	The data were extracted in other moments that were unrelated to injuries, performance, and/or talent.
Additional criteria	Only original and full-text studies written in English	Written in languages other than English. Article types different from original (e.g., reviews, conference abstracts, etc.).

by the two authors (MRG and JPO). Additionally, they reviewed the full version of the included papers in detail to identify articles that met the selection criteria. An additional search within the reference lists of the included records was conducted to retrieve additional relevant studies. A discussion was conducted with a third author (AMZ) in cases of discrepancies regarding the selection process. Possible errata for the included articles were considered.

Data Extraction

A data extraction was prepared in Microsoft Excel (Microsoft Corporation, Readmon, WA, USA) in accordance with the Cochrane Consumers and Communication Review Group's data extraction template [30]. The Excel sheet was used to assess inclusion requirements and subsequently tested for all selected studies. The process was independently conducted by the two authors (MRG and JPO). Any disagreement regarding study eligibility was resolved in a discussion. Any full-text articles excluded, with reasons, were recorded. All records were stored in the datasheet.

Data items

The following information was extracted from the included original articles: (1) participants (number of teams, number of matches, number of attempts); (2) data acquisition source/technology; (3) attributes, variables, or features; (4) aim of prediction; (5) ML issues (approach, algorithms, and prediction %); and concluding remarks and predicting.

Methodological Assessment

A methodological assessment process was performed by the two authors (JPO and MRG) using an adapted version of the STROBE assessment criteria for cross-sectional studies [31], looking for studies eligible for inclusion. Each article was assessed based on 10 specific criteria: provide in the abstract an informative and balanced summary of what was done and what was found (Item 1); state specific objectives, including any prespecified hypotheses (Item 2); Give the eligibility criteria, and the sources and methods of selection of participants (Item 3); for each variable of interest, give sources of data

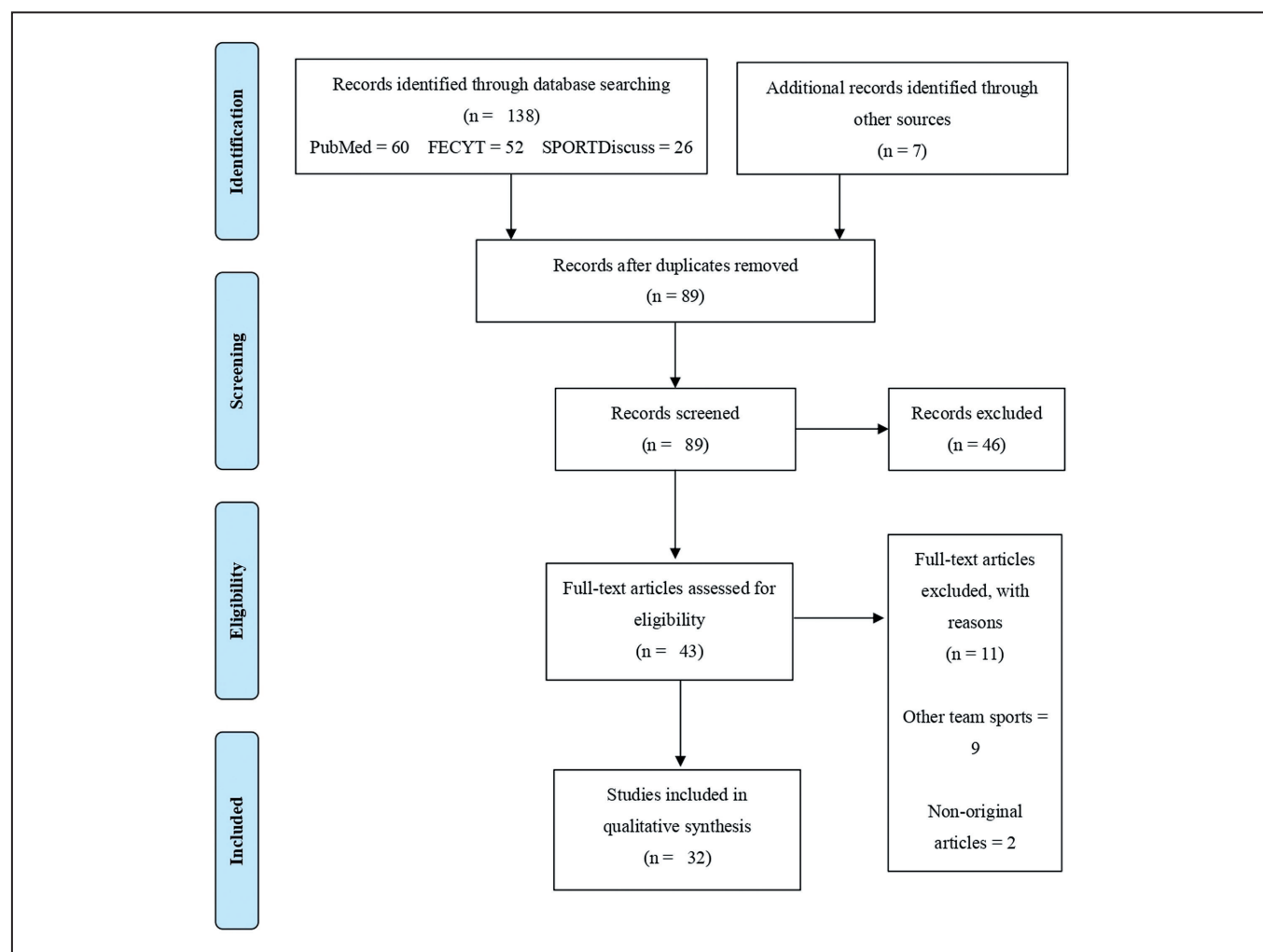


FIG. 1. Flow diagram of the selection of studies.

and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group (Item 4); explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why (Item 5); give characteristics of study participants (Item 6); summarize key results with reference to study objectives (Item 7); discuss limitations of the study, considering sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias (Item 8); give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence (Item 9); give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based (Item 10).

Any disagreement was discussed and solved by consensus decision. Each item was evaluated using numerical characterization (1 = completed; and, 0 = incomplete). As suggested by O'Reilly et al. [31], each study rating was qualitatively interpreted according to the following law: the study has a risk of bias or low quality with

a lower punctuation value than 7 points, while those studies with greater punctuation are considered as having a low risk of bias or as high quality.

RESULTS

Study identification and selection

The searching of databases identified a total of 138 titles (PubMed = 60; FECYT = 52; SPORTDiscus = 26). In addition, 7 studies were included from external sources. These studies were then exported to reference manager software (EndNote™ X9, Clarivate Analytics, Philadelphia, PA, USA). Duplicates (56 references) were subsequently removed either automatically or manually. The remaining 89 articles were screened for their relevance based on titles and abstracts, resulting in the removal of a further 46 studies. Following the screening procedure, 43 articles were selected for in-depth reading and analysis. After reading full texts, a further 11 studies were excluded due to not meeting the eligibility criteria. Finally, 32 studies were included in the qualitative synthesis (Figure 1).

TABLE 2. Methodological assessment of the included studies.

Reference	1	2	3	4	5	6	7	8	9	10	Quality
Ayala et al. [2]	1	1	1	1	1	1	1	1	1	1	High
Barron et al. [8]	1	0	1	1	1	0	1	1	1	1	High
Bialkowski et al. [22]	1	0	0	1	1	0	1	1	0	1	Low
Bilek and Ulas [7]	1	0	1	1	1	1	1	0	1	0	Low
Bongiovanni et al. [48]	1	0	1	1	1	1	1	1	0	0	Low
Brooks et al. [20]	1	1	1	1	1	0	1	1	1	1	High
Campbell et al. [5]	1	0	0	1	1	0	1	1	1	0	Low
Chawla et al. [16]	1	0	1	1	1	0	1	1	1	0	Low
Ćwiklinski et al. [9]	1	0	0	1	1	0	1	0	1	1	Low
DiCesare et al. [18]	1	1	1	1	1	1	1	1	1	1	High
Dick and Brefeld [32]	1	0	1	1	1	0	1	0	1	1	Low
García-Aliaga et al. [33]	1	0	1	1	1	1	1	0	1	1	High
Geurkink et al. [34]	1	0	1	1	1	1	1	1	0	0	Low
Goes et al. [46]	1	1	1	1	1	0	1	1	1	1	High
Goes et al. [17]	1	1	1	1	1	0	1	1	0	1	High
Jaspers et al. [35]	1	0	1	1	1	1	1	1	1	1	High
Joseph et al. [23]	1	0	1	1	1	0	1	1	1	0	Low
Knauf et al. [36]	1	0	1	1	1	1	1	0	0	0	Low
Leser et al. [37]	1	0	1	1	1	1	1	1	1	1	High
Link and Hoering [38]	1	0	1	1	1	0	1	1	0	1	Low
López-Valenciano et al. [3]	1	0	1	1	1	1	1	1	1	1	High
Montoliu et al. [39]	1	0	1	1	1	0	1	1	0	0	Low
Oliver et al. [4]	1	0	1	1	1	1	1	0	1	1	High
Op De Beéck et al. [40]	1	0	1	1	1	1	1	1	1	0	High
Pappalardo and Cintia [6]	1	0	1	1	1	0	1	1	1	1	High
Perri et al. [21]											<i>Full text not found</i>
Rodas et al. [15]											<i>Full text not found</i>
Rommers et al. [41]	1	0	1	1	1	1	1	1	1	1	High
Rossi et al. [19]	1	0	1	1	1	1	1	0	0	1	Low
Sheng et al. [10]	1	0	0	1	1	0	1	0	1	0	Low
Szczepański and McHale [42]	1	1	1	1	1	0	1	0	1	1	High
Zago et al. [43]	1	1	1	1	1	1	1	1	1	1	High

Methodological quality

The overall methodological quality of the studies can be found in Table 2.

Characteristics of individual studies

The characteristics of studies were extracted and clustered into three tables: ML and injuries (Table 3), ML and performance (Table 4), and ML and talent identification (Table 5).

TABLE 3. Studies that used ML to predict injuries in soccer.

Ref.	Participants	Data acquisition technology	Attributes/ Features/ Variables	Aim of prediction	Machine Learning			Practical application from predicting
					ML Approach	Algorithm	Accuracy	
Ayala et al. [2]	96 professionals from 4 teams (1 st , 2 nd). 18 injuries during 1 pre-season.	Surveys + Tools for biomechanical test	Personal risk factors (playing position, dominant leg, etc.) + Psychological risk factors (sleep diary and burnout) + Neuromuscular risk factors (postural, ROM, stability, flexibility)	Hamstring strain injuries (HIS)	Supervised	ADTree	> 78%	Sleep quality, history of HIS last season, hip flexion ROM (joint ranges of motion), and the angle of peak torque measured during eccentric (hamstrings) knee extension movements is important for predicting in-season HIS.
DiCesare et al. [18]	75 players from high-school academies (17 games)	Video recording + MEMS (accelerometer)	Head impacts	Brain change derived from these actions	–	Extreme Gradient Booster (XGBoost) based on trees classifier	> 83%	The number of head impacts can predict changes in the brain through longitudinal ML algorithms.
López-Valenciano et al. [3]	98 professional (1 st and 2 nd) players from 4 teams	Tools for biomechanical test (Y-balance device, dynamometer) + Personal (playing position, dominant leg, etc.) and psychological (sleep quality and burnout) surveys	Personal risk factors (playing position, dominant leg, etc.) + Psychological risk factors (sleep diary and burnout) + Neuromuscular risk factors (postural, ROM, stability, flexibility)	Lower extremity muscle injuries	Supervised	4 decision tree algorithms: C4.5 SimpleCart ADTree RandomTree	> 66%	The presented model could moderately help coaches in decision-making and training design to reduce the number and severity of muscle injuries.
Oliver et al. [4]	355 youths (from 10 to 18 years old) during 1 season.	Tools for biomechanical test	Injury incidence during 1 season + Pre-season screen: anthropometric, single leg CMJ and leg hop for distance, Y-balance, and tuck jump.	Neuromuscular injuries	Supervised	Decision trees: J48 consolidated. Alternative decision tree. Reduces error pruning tree.	74%	Asymmetry in single leg CMJ, 75% hop distance and stick, Y-balance, plus tuck jump knee valgus and anthropometrics are the most frequent contributors to predicting injury incidences.
Rommers et al. [41]	734 U10 and U15 players during 1 season (with half of the players sustaining 1 injury)	–	Injury incidence during 1 season + Pre-season screen: anthropometric (height, weight, and sitting height) and physical fitness (strength, flexibility, speed, agility, and endurance)	Injuries from overuse or acute from pre-season results	–	Extreme gradient boosting algorithm (XGBoost)	78–85%	Proposed ML models could identify youth players with the highest injury risk.
Rossi et al. [19]	26 professionals during 1 season (931 sessions for 23 weeks)	GPS + MEMS (both from STATSports)	23 non-contact injuries were registered. + Personal features (considering previous injuries) + 12 training load variables	Injuries from overuse or acute	Supervised	Decision tree	70–100%	A previous injury can lead to another when: Training HSR > 112 m. Training HSR > 112 m and total distance monotony 3 times lower than 1.78. Training HSR > 112 m and total distance monotony 2.5 times higher than the player's average.

TABLE 3. Continue.

Ref.	Participants	Data acquisition technology	Attributes/ Features/ Variables	Aim of prediction	Machine Learning			Practical application from predicting
					ML Approach	Algorithm	Accuracy	
Rodas et al. [15]	363 from different team sports (including soccer) from FC Barcelona during 10 leagues (55% with injury)	—	Injury attempts + Genetic markers (proteins, single nucleotide polymorphisms, genes)	Tendinopathy injuries	Supervised	Support vector machine	—	Through the analysis of genes tendinopathies can be predict.
			Random forest			One of the most robust single nucleotide polymorphisms was rs10477683 in the fibrillin 2 gene encoding fibrillin 2.		

Note = ANN: artificial neural network; MC4: BN: Bayesian Networks; HIS: hamstring strain injuries; IMU: inertial measurement unit; KNN: K-nearest neighbor; MC4 Decision trees;

TABLE 4. Studies that used ML to predict performance in soccer.

Ref.	Participants	Data acquisition technology	Attributes/ Features/ Variables	Aim of prediction	Machine Learning			Practical application from predicting	
					ML Approach	Algorithm	Training algorithm		Accuracy
Match/League outcomes predicting									
Blek and Ulas [7]	20 professional teams from English Premier League during a season (380 games)	Observation	22 situation/ performance variables: Result, match location, scoring first, cards (yellow/red) and 16 technical variables (passes, shots, tackles, possession %)	Match outcome (win, draw, loss)	Supervised	K-means Clusters Decision trees		68–78%	To predict match outcomes, the most important variable is scoring first, and its influence depends on the quality of opposition.
Dick and Brefeld [32]	5 elite European soccer games (380 successful and 715 non-successful attacks)	Tracking system	Team in possession + Players positioning (x/y coordinates) + Game in play or halted	What game situations have a great potential to achieve successful attacks (the ball has a lower distance than 25 m from opponent team’s goal)	—	Deep reinforcement learning	Adam optimization algorithm	—	The presented deep reinforcement learning may be used to evaluate multiplayer positioning from positional data. They hypothesized that this model could be of interest to measure, together with playing speed and passes, what type of attack could predict a great success (counterattack or using cross passes).
Goes et al. [46]	26 professional teams during 4 seasons (1237 successful and 11187 unsuccessful attacks)	Semi-automat-ic camera system	Own GC — opponent GC Own defenders’ GC — Own midfielders’ GC The relative phase of these variables (synchronization)	Successful attacks from collective tactical variables	Unsuper-vised	K-means	—		Sub-group variables (GC-GC between 2 subgroups within a team) is more sensible than team level analysis (GC-GC) to predict successful attacks. Successful attacks strongly depend on both defenders creating space for the attackers and their synchronization with midfielders’ GC.
Leser et al. [37]	20 U15 players during 279 SSG (3 vs. 2)	Camera + Tracking system + MEMS	30 technical/tactical parameters during two situations: 1. The time instant of the shot. 2. The time instant of the last action before the shot.	The efficiency of tactical patterns	Unsuper-vised	Clustering techniques	—	—	The participation of each player in each attacking pattern can be considered. As a goal in each attacking pattern was noted, the proportion of goals that is expected by each player can be identified.
Joseph et al. [23]	2 seasons, 76 matches from English 1 st division Tottenham team (Premier League)	—	30 attributes. + Players, venue, and opponent quality.	Match outcomes (win, lose, or draw). Attacking force. Overall team quality. Team performance knowing own/opp. quality.	—	Expert constructed BN Naïve BN Hugin BN MC4 KNN		From 50 to 59%	What among the selected attributes are the crucial factors affecting the outcome of a game and give some clues as to the relationships between some of those factors.

TABLE 4. Continue.

Ref.	Participants	Data	Attributes/ Features/ Variables	Aim of prediction	Machine Learning			Practical application from predicting		
		acquisition technology			ML Approach	Algorithm	Training algorithm		Accuracy	
Brooks et al. [20]	20 teams from Spanish 1 st division during 80% of matches from 1 season.	Camera (Opta Sports)	Pass location							
			The time of the pass							
			Team that made the pass	The success of						
			Player that made the pass	attacks (what						
			Intended pass recipient	attacks end in						
			The origin of the pass	a shot on goal)						
			Possessions (> 3 passes)	The players with	Supervised	KNN	Cross-validation	87%		
			% of passes in a possession that originate in a particular zone	a greater possibility						
Pappalardo and Cintia [6]	6396 games and 10 million events from 6 European professional leagues (145 clubs) during 3 seasons	—	% of passes in a possession that have a destination in a particular zone	through average						
			% of passes in a possession from one zone to another zone	pass shot value						
			Events (pass, shot, tackle, take-on, clearance, intercept, cross, foul, aerial duel, and goalkeeping)	Match and league	Supervised	Random forest	—	Gener-al < 80% Draws 26%		
			Team and player who generated the event	ranking outcomes						
			Events' positioning							
			Timestamp of the event							
Physical/physiological performance predicting										
Bongiovanni et al. [48]	16 U15 from Italian professional club	Tools to measure anthropometric + Timing gates for yo-yo, 10 and 20 m sprint, 90° change of direction test, and CMJ	16 anthropometric measures							
			+	Aimed to predict						
			5 created combining from 2 to 9 of these 16 initials	performance from	—	Extra tree regression		High accuracy		
			+	anthropometric						
			Physical performance from tests	variables						
Campbell et al. [5]	7918 observations after data cleaning during 2013–2018 seasons	RPE and wellness surveys + GPS	8 wellness variables	Aimed to predict		Classification				
			+	training load from		tree				
			iTL (RPE)	wellness	Supervised	Regression		> 89%		
			+	questionnaires		tree				
			eTL (total distance and m/min)			Random forest				
Geurkink et al. [34]	46 non-professional players during 2 seasons (61 training sessions)	GPS + Heart rate devices	70 iTL, eTL, personal, and supplementary variables.	Session RPE	—	Gradient Boosting Machines		MAE: 0.67 ± 0.09 RMSE: 0.93 ± 0.16	eTL indicators (mainly total distance covered) are the stronger RPE predictors, although including a broad range of variables, other than ELIs, may be useful.	
Jaspers et al. [35]	38 professionals from 1 st Netherlands division during 2 seasons.	RPE survey	iTL indicators (RPE)						LASSO and ANN can predict RPE based on a large set of e TL variables.	
		+	+							
		GPS	67 eTL indicators	RPE	—	ANN LASSO	—	Lasso more precision than ANN	Accelerations were important eTL variables to predict RPE.	
Op De Beéck et al. [40]	26 professionals during a season (pre- and in- season)	RPE survey, MEMS and GPS	Total amount not specified			Gradient boosted regression tree.			A combination of eTL, iTL, and pre-season perceived wellness may indicate importance in a broad monitoring approach for performance prediction.	
				Wellness	—	Naive baseline.		> 70%		

TABLE 4. Continue.

Ref.	Participants	Data acquisition technology	Attributes/ Features/ Variables	Aim of prediction	Machine Learning				Practical application from predicting
					ML Approach	Algorithm	Training algorithm	Accuracy	
Perri <i>et al.</i> [21]	28 sub-elite players	Surveys	RPE Training time Wellness index	Match performance according to wellness index and RPE	Supervised	Regression	—	39%	ML can predict the wellness according to the load performed the day before. The ML model can be used to predict the wellness based on a targeted weekly load.
Zago <i>et al.</i> [43]	13 elite females in a shuttle run test	MEMS (accelerometer, gyroscopes, and barometer)	18 features (predictors)	Turn direction Speed (before and after turn) Mechanical load during turns	Supervised	Linear regression Support vector regression Boosted decision trees ANN	—	> 98.4%	Although models can be extended to different angles, we showed that meaningful information on turn kinematics and energetics can be obtained from inertial units with a data-driven approach.
Technical/tactical performance predicting									
Chawla <i>et al.</i> [16]	English 1 st division Arsenal team during 4 matches (2932 passes)	Video camera and human observers	Players' trajectories + Sequence of events (touch, pass, shot, tackle, goal, etc) + Mapping of players to their respective teams (dominant regions)	Pass event	Supervised	RUSBoost classifier Multinomial logistic regression	—	> 90%	Considering current events, current location of all players may be possibly predict the quality of passes.
Szczepatalski and McHale [42]	760 matches during 2 seasons of English Premier League's 20 teams and/or 481 players (253090 events)	Camera (Opta Sports)	Each player's inherent player skill in a certain context. Factors that influence the probability of a pass being successful	Predict passing completion rate for the next season from the present passing completion rate.	—	Naive	—	—	This method can be used to evaluate passing skill depending on the difficulty of each attempt.
Goes <i>et al.</i> [17]	18 Dutch 1 st division matches from 13 teams during 1 season (16943 passes from which 10481 were received)	Semi-automat-ic video camera (SportVU, STATS)	Centroids Pass (length, velocity) angle Convex hull Spread Move of defensive players	Pass effectiveness	Supervised	RUSBoost classifier	—	85%	Pass success can be predicted from tactical approaches.
Link and Hoering [38]	60 matches from German Bundesliga (69,667 individual ball actions)	Semi-automat-ic camera system (TRACAB)	Positional data + Kick detention intervals to know: Team ball possession (a sum of individual possessions) Individual (a player) ball possession. Individual ball actions. Individual ball control. Team ball control. Team ball control without void passes.	Time that ball is in the sphere of influence of a player	—	Bayesian network	K2 algo-rithm [12]	Ball control 97% Without ball 50% K = 0.67	Proposed model can predict how long the ball will spend in the sphere of influence of a player based on the distance between the players and the ball together with their direction of motion, speed, and the acceleration of the ball.
Montoliu <i>et al.</i> [39]	4 teams from Spanish 1 st division League during 2 seasons	Camera	Ball possessions (attacks) Quick attacking actions (passing and moving, switching the attack, and fast break) Set pieces (direct free, indirect free, penalty, and corner kicks)	Classify ball possession, quick attacks, and set pieces (strategies)	Supervised	K-Nearest neighbor Support Vector Machine Random Forest	Back propaga-tion [13]	67–93% Random Forest is the classifier obtaining the best classification results.	This approach can cluster team behavior into three types (ball possession, fast attack, or strategy) and to recognize the most common play patterns when playing a match.

TABLE 4. Continue.

Ref.	Participants	Data acquisition technology	Attributes/ Features/ Variables	Aim of prediction	Machine Learning			Practical application from predicting
					ML Approach	Algorithm	Accuracy	
Bialkowski et al. [22]	374 matches from 20 teams.	Semi-Automated camera system (Prozone).	Player location 43 events (passes, shots, crosses, tackles etc.)	Team structures	Unsupervised	Expectation maximization algorithm [43] (Similar to k-means clustering).	70%. Three times better than other traditional methods (descriptive statistic, etc.)	Team formation clustering as a strong descriptor for identifying a team's style. Assigns players to roles. It can be known when a player is in the left-wing position compared to left back.
		Handle note.						
Knauf et al. [36]	10 games. 5 from 1 st and 5 from 2 nd division of Bundesliga during 1 season. (31,000,000 positionings)	Camera (VIS. TRACK)	Players and ball trajectories Sequence initiation by goalkeeper Scoring opportunities (3/4 of field)	Team patterns	Unsupervised	k-medoids cluster		Through this clustering method, the player trajectories predicting how chaotic a team is or how many patterns (solution categories, quick/slow attacks with more and/or lower passes) are performed.

Note = ANN: artificial neural network; MC4: BN: Bayesian Networks; IMU: inertial measurement unit; KNN: K-nearest neighbor; MC4 Decision trees; LASSO: least absolute shrinkage and selection operator; RIPPER: Repeated Incremental Pruning Produce Error Reduction algorithm;

TABLE 5. Studies that used ML to predict talents in soccer.

Ref.	Participants	Data acquisition technology	Attributes/ Features/ Variables	Aim of prediction	Machine Learning			Practical application from predicting
					ML Approach	Algorithm	Accuracy	
Talent identification								
Barron et al. [8]	966 players (low level: 209; Football League Championships: 637; English premier league: 120)	ProZone´ s MatchViewer system	347 technical indicators: total number, accuracy, and consistency of passes, tackles, possessions regained, clearances, and shots.	Using data set from previous seasons, the aim was to know the level of a player, comparing where he played in the following seasons after data recording.	—	ANN	61–79%	From data set recorded in the previous seasons, proposed ML could predict where the player will play in the following seasons (in lower leagues, championship, or English Premier League). ANN can accurately predict the career trajectory of a player.
Sheng et al. [10]	13 th Chinese national games data as well as the training matches data of the Shanghai U20 soccer team	Tracking camera	Technical actions (iceberg figure) + Players´ positioning (heat map)	Select most potential players	—	GreenSea broad learning system	—	Using this model, game analysis could help coaches in decision-making regarding players with the most potential and their improvement.
Player transferences								
Ćwikliński et al. [9]	4700 players from 156 clubs belonging to the eight most popular leagues	Notation	29 technical variables + 7 psychological variables + 4 outcome variables (matches played, won, etc.)	The aim was to predict if a player transferal between two teams is successful (successful = player performance was (i) up from the previous season before transference and (ii) above the mean of his new team.	—	Random forest Naïve Bayes AdaBoost	—	A model can predict if a player will be a successful transfer based on some technical, psychological, and physical (outcome) variables.
Identification of lineups issues								
García-Alaiga et al. [33]	Matches over 7 seasons from 18 national leagues. A total of 50,000 matches and 30,000 players.	Tracking camera (OPTA)	Individual technical-tactical features	Players´ playing position based on technical/ tactical features	Supervised	RIPPER	> 73%	The ML has the potential to predict a player´s most suitable playing position based on his/her technical-tactical performance.
Sheng et al. [10]	13 th Chinese national games data as well as the training matches data from the Shanghai U20 soccer team	Tracking camera	Technical actions (iceberg figure) + Players´ positioning (heat map)	Analyze games and make team tactics	—	GreenSea broad learning system	—	Using this model, game analysis could help coaches in decision-making regarding the team tactics.

Note = ANN: artificial neural network; MC4: BN: Bayesian Networks; IMU: inertial measurement unit; KNN: K-nearest neighbor; MC4 Decision trees;

DISCUSSION

The present systematic review was to systematically identify original studies that applied ML with soccer data, highlighting current possibilities in ML and future applications. The main findings were: (1) the best attempts at predicting injury incidences are derived from pre-season screening, training load, genetics, or risk factor surveys (personal, psychological, and neuromuscular), that through algorithms such as decision trees can predict injury risk at an accuracy greater than 66%; (2) performance predictive ML models were used in three ways: predicting outcomes, physical/physiological performance, and technical/tactical performance. (2.1) notational analysis and positional data can lead to predicting through ML the match outcomes or even the final ranking of a league. (2.2) ML approaches can help to identify the best contributors and determinants to explain wellness and training load magnitudes and that eventually can give some important orientations to coaches. (2.3) technical and tactical inputs can reveal the passing effectiveness and classify team styles through the ML algorithms. (3) Finally, ML algorithms can lead to predicting a young talent, predicting a player's successful transferal between teams, and the most suitable configuration of starter players for a competition, mainly using technical and positional data as input.

In soccer, the laws establish a framework of action that, in a certain way, guides players performance beforehand [44]. However, soccer game dynamic, where two teams play against with the same objective but on opposite sides, allows players to perform a wide range of actions, only allowing for the possibility of hypothesizing about what is going to happen [45]. In this sense, coaches are involved in a decision-making game, in which actions are taken that, despite being based on tracking objective data, necessarily have to be intuitive due to the unpredictability of events. However, technological development has allowed the arrival of prediction algorithms (e.g., ML), which has made use of the large amount of data recorded and storage available, becoming them as input, and making "learning" processes possible in order to base outputs into a large amount of data stored, allowing the possibility of what is going to happen to be anticipated in three aspects: (1) injury prevention, (2) performance, and (3) talent identification.

Injury prevention predicting

Due to the expensive process of recovery and rehabilitation for players, as well as the seasonal costs of medical care, injury involves a great economic cost to a soccer club. For example, Rossi *et al.* [19] estimated a minimum of 11,583 euros/player is spent during a season (931 sessions performed during 23 weeks) by a professional soccer club. In this sense, the newly developed potential to anticipate the future has encouraged sport scientists to use ML prediction models to try and help coaches in decision-making and training design, with the aim of reducing the number of severe muscle injuries [2, 3, 18, 41] and of highlighting the most predictive features in this field [4, 15, 19].

The proposed ML algorithms were mainly based on decision trees (ADTress [2], XGBoost based on trees classifiers [18, 41], C4.5.,

SimpleCart, ADTree, and Random Tree [3], and J48 consolidated, reduced error punning tree, and alternative decision trees [4]), although Support Vector Machine and Random Forest were also considered for injury predicting [15]. The inputs were based on injury incidences and personal, psychological, and neuromuscular risk factors [2, 3]; pre-season anthropometrics (height, weight, and sitting height) and physical fitness (strength, flexibility, speed, agility, and endurance) screening [4]; and training load (distance covered at different intensities (total distance, high speed running (HSR) and explosive distance), metabolic load related features, accelerations/decelerations, dynamic stress, and fatigue index) [19]. For example, Ayala *et al.* [2] through a supervised ADTree and personal, psychological, and neuromuscular features predict more than 78% of strain injury occurrences, while Rommers *et al.* [41] proposed a model which predicted, with 78–85% of predictive attempts, players that had the highest injury risk. All these authors, like López-Valenciano *et al.* [3] making possible the application of ML to injury risk management strategies in order to reduce muscle injury incidence, or even, to predict changes in a certain part of players' body such as DiCesare *et al.* [18], who proposed that through XGBoost based on trees classifier, with more than 83% of prediction attempts, it can be predicted the longitudinal changes in the brain caused by head impacts. These ideas may only lead to the highlighting of ML as an option to reduce injury incidences (following these proposals with a greater accuracy than 66% of prediction attempts), offering crucial information that may be used for training design strategies during the certain moments or with certain players that have a greater likelihood of suffering injuries.

Furthermore, some authors have tried to point out more specific indications, highlighting the most frequent contributors to the prediction of injury incidences [4, 15] or practical applications [19]. Specifically, Rodas *et al.* [15] analyzed 363 players from different team sports (including soccer) from FC Barcelona (Spain), and highlighted that using data about injury incidences and genetic markers (proteins, single nucleotide polymorphisms, genes) may predict tendinopathy injuries. Specifically, the authors found that one of the most robust single nucleotide polymorphisms to predict tendinopathies was rs10477683 in the fibrillin 2 gene encoding fibrillin 2, a component of connective tissue microfibrils involved in elastic fiber assembly [15]. However, due to the impossibility of using these inputs for most teams – mainly non-professional teams – the use of pre-season screening may be a more achievable strategy. In fact, Oliver *et al.* [4] have highlighted that a single leg counter movement jump, 75% hop distance and stick, Y-balance, plus tuck jump knee valgus, and anthropometric features are the major predictors for injury incidences; at least with young soccer players. Beyond, and not only considering a prediction test in the initial stages of a season, Rossi *et al.* [19] emphasized some conditions that through popular and widely used tracking systems may be considered. Specially, the authors highlighted that a previous injury can lead to another when: (1) training HSR is > 112 per/min; (2) training HSR is > 112 m/min

and total distance monotony is three times lower than 1.78; and (3) training HSR is > 112 m/min and total distance monotony is 2.5 times higher than the player's average. Therefore, these practical applications may be used by clubs to predict injury incidences and their negative consequences.

In summary, data about injury incidences, together with other additional variables such as pre-season screening, training load, genetics, or risk factor surveys (personal, psychological, and neuromuscular), may be used as inputs to predict injury incidences through ML algorithms such as decision trees, which have been the most used algorithms for injury prevention. Practically, performing a pre-season test, or even if possible the use of tracking systems and the analysis of genetic markers, may be useful to predict players or situations with a higher percentage of injury risk.

Performance predicting

Match/League outcomes predicting

Among the seven included articles [6, 7, 20, 23, 32, 37, 46] focused in the use of ML in match performance, five of them were able to produce an accurate prediction regarding the match performance [6, 7, 20, 23, 46]. The studies of Bilek and Ulas [7], Joseph et al. [23], and Pappalardo and Cintia [6] made prediction attempts regarding the match outcome, while the studies of Goes et al. [46] and Brooks et al. [20] attempted to predict the successful attacks. Without a prediction attempt, the studies of Dick and Brefeld [32] and Leser et al. [37] focused on detecting the situations with a high potential of success and on analyzing the efficiency of tactical patterns, respectively.

The approach used by the studies conducted to predict the match outcome were different; namely considering the usable variables [6, 7, 23]. While the studies of Bilek and Ulas [7] and Pappalardo and Cinti [6] have focused on regular notational analysis events (e.g., passes, shots, possession), the study of Joseph et al. [23] was centered on the presence of specific players, the quality of the opposing team or the venue. Using the k-means, clusters and decision trees, the study of Bilek and Ulas [7] using 22 situational variables from 380 games and 760 observations in the English Premier League was able to predict match outcomes with between 68 and 78%, in which it was found that situational variables and match results were determinant. Interestingly, it was revealed that scoring first and the quality of opposition was determinant [7]. In another study considering 6000 games and 10 million events in six European leagues, it was found that victory and defeat can also be explained with team's performance, and that final league position is also dependent on technical performance [6]. Interestingly, both studies [6, 7] have revealed a clear link between match outcomes and technical performance.

Looking for classification of attacking situations, and using classical notational events (e.g., pass, possession, pass location), the study conducted by Brooks et al. [20] on Spanish teams allowed passes to be classified in heat maps, and from those the patterns of

the teams to be detected and the KNN model to be run. The study concluded that the locations of the origins and destinations of passes in a possession are correlate highly to whether that possession will end in a shot [20]. However, technical performance measures are just another product or outcome, which may not be the best information to adjust the training process [47]. Measures related to processes identifying which behaviors can be conducive to better efficacy and ultimately to performance should be also considered. Thus, considering the use of the bi-dimensional analysis of player relationships, the study of Goes et al. [46] classified successful attacks by taking into consideration the relationship between the geometrical centers of both teams and the synchronization level. Using a sample of 11187 attacks (successful and unsuccessful), from the results it was possible to identify that successful attacks were related to decreases in the synchrony of intra-team and inter-team subgroup analysis, thus with the creation of space [46].

Using a mixed approach between classical notational measures and information related to player positioning in the Cartesian space, the study of Dick and Brefeld [32] revealed that the implemented model was able to evaluate multiplayer positioning based on positional data and that attacking can be predicted for its efficacy by adding information about playing speed and passes. Additionally, the study of Leser et al. [37] allowed the identification that offense attempts have the highest scoring probability when played exploring the wings near to the goal lines and when the final pass, before the shot, is given against the direction of play.

In brief, the included studies about predicting match outcomes had focused on two main aspects: predicting the match outcome by using classical notational variables and identifying the efficacy of attacks by considering notational analysis events and positioning data from the players. The studies considering the efficacy of actions were focused on attack [6, 7, 20, 32, 37]. Future studies should focus on defensive processes, namely focusing on considering behaviors that are conducive to success and not only on events (product measures).

Physical/physiological performance predicting

From the included articles in this section, one study focused on determining the capacity of anthropometry to influence physical performance [48], three studies related wellness data with training load and match performance [5, 21, 40], two studies tested the prediction of rate of perceived exertion (RPE) based on training load measures [34, 46] and one focused on using inertial units to identify the kinematics and energetics of player demands [43].

Regarding the use of extra tree regression for determining the contribution of soccer players' anthropometric features to predict their physical performance, it was possible to ascertain the determinacy of these features for sprinting and aerobic fitness [48]. Despite the small sample used, it was also possible to conclude that machine learning can be used to identify the importance of a specific measure to predict a player's performance [48]. Naturally, more studies

should be conducted, and with greater samples. Eventually, comparison between prediction methods should also be considered.

Regarding the studies focusing on wellbeing parameters and the relationship with training load and match performance, the study conducted by Campbell *et al.* [5] revealed a limited predictive capacity of wellness to determine internal and external load, even considering different approaches (regression, classification and random forest models). The findings also allowed the suggestion that new wellness questionnaires should be considered to test the sensitivity to training load or vice versa, since a previous systematic review also confirmed that wellness and training load are minimally to slightly related [49]. Changing the approach, a study conducted on 26 professional players tried to predict perceived wellness based on preceding load and perceived wellness using individual machine learning models [40]. The analysis revealed that the combination of training load parameters with preceding perceived wellness resulted in the best predictive performance and that using cumulative load did not improve the predictions. This study also suggests implementing wellness questionnaires as part of a well-implemented monitoring strategy [40]. Also testing the influence of match load on wellness, a study conducted on sub-elite players [21] revealed the importance of match load in wellness responses, thus confirming the relevance of impact on fatigue. Therefore, among these three wellness-related articles [5, 21, 40] it is possible to argue for the sensitivity of wellness to training and match load, but that there is a lack of relevance on the demands and training load.

Testing the relationships between different training load measures, two studies have used machine learning to predict the RPE [34, 35]. In a study conducted over two seasons using a sample of 61 training sessions [34], it was possible to identify that from different external load measures, distance covered was the best predictor of RPE, despite internal load measures (heart rate zones, training impulse) being the strongest predictors of the session-RPE [34]. Also using machine learning to determine relationships between external and internal load measures, it was possible to find that RPE was predicted by both internal and external load measures, namely considering high-magnitude decelerations [35]. Therefore, it seems that session-RPE (a perceptive scale) is highly capable of connecting information and dependency from objective measurements from internal and external load.

In summary, it is possible to conclude that ML approaches can help to identify the best contributors and determinants to explain wellness and training load magnitudes, and this eventually can help in the future to reduce the amount of data collected and improve the efficacy of the monitoring process in players. Additionally, it can be expected that ML may help to determine the best predictors of athletic performance, thus giving some important orientations to coaches.

Technical/tactical performance predicting

Among the included studies, three of them were focused on identifying the effectiveness of passes [16, 17, 42], two on identifying ball possession and circulation [39, 40], and two on classifying

the team's patterns of play [22, 36]. Five of the studies tested predictions [16, 17, 22, 38, 39]. Regarding the studies that proposed to identify the effectiveness of passes, one of them [16] proposed a model able to learn a classifier to rate the quality of passes with an accuracy of 85%, revealing that machine learning had similar efficacy to a human observer. With a different aim, the study of Szczepański and McHale [42] tested the capacity to estimate each player's passing skill and make predictions for the next season. The model implemented in that study revealed a good capacity to predict the next season's completion rate based on the past, and that variations in the difficulty of passes attempted in both seasons had a determinant impact in the observed performance of some players [42]. Not using observational actions but using information from position data and geometrical interactions between players, and considering 16943 passes [17], it was possible to classify how well a pass disrupts the opposing defense. Despite the advances in this field of detecting passes, interaction between different kinds of measures should be considered; namely integrating data from events and position data about collective dynamics that lead to pass success.

Analysis of process and outcomes is necessary, mainly to explain how teams behave. Considering positional data and team ball possession, a study conducted in the German Bundesliga [38] described models for detecting individual and team ball possession. The model proposed was able to determine individual possession and consider the time spent in different regions of the pitch based on distance between players and their direction of motion, speed and the acceleration of the ball [38]. Interestingly, it was found by the authors that individual ball possession influenced passes, tackles and shots on goal [38]. In another study also focusing on ball possession [39], it was found that information about number of ball possession, attacking actions and set pieces (direct free, indirect free, penalty, and corner kick) was able to classify the team's behavior in three categories: ball possession (low pace), fast attack or strategy. Among the models tested, the random forest was the one allowing the best classification result, even considering comparisons with neural network-based methods [38].

Also considering the classification of team behavior, a study conducted over 374 matches [22] analyzed player tracking data to describe the formation of the team. Using an expectation maximization algorithm it was possible to assign players to a role and classify the team's formation [22]. In a different approach, a study conducted over 10 matches [36] used the k-medoids cluster to analyze the chaotic level of the teams and the different patterns emerging from the match considering player trajectories.

In summary, the research using machine learning for technical/tactical performance reveals the capacity of models to predict the passing effectiveness and to classify team styles. This can be interesting for a future automatic analysis about the behaviors of the teams and for exporting interpretations for coaches to adjust the training drills to the needs of the teams.

Talent identification

The current trend focusing on talent has defined which term as a dynamically varying relationship molded by the constraints imposed by the physical and social environments, the task experienced, and the personal resources of a player [50], highlighting talent identification in one of the more important challenges in soccer, not only during early ages [8, 10], but also for player transferal between soccer clubs [9]. In addition, ML can be used in this way to predict the most suitable players for decision-making for competition starter players (choosing players and playing positions) [10, 33].

To date, it has been systematically reviewed that technical and time-motion variables are clustered into principal components that explain the behavior of soccer players [51]. Based on these ideas, the most used inputs (features) to identify the talent of soccer players are technical variables such as passes, tackles, possessions, clearances, or shots [8–10], as well as variables extracted from tracking systems [10], and psychological indicators [9]. For example, Barron et al. [8] analyzed 966 soccer players (209 from low level, 637 for Championship Football League, and 120 from English Premier League), and with an accuracy of between 61 and 79% of attempts, the authors predicting players' career trajectory using 347 technical attributes. Similarly, Sheng et al. [10] assessed a ML algorithm (Green-Sea broad learning system) highlighting the potential of the model to predict the players with the most potential and their improvement. However, talent identification is not only supposedly relevant with young soccer players, but also for professional players. For example, Real Madrid, based on seven successful seasons that Eden Hazard performed, contracted the player with one of the most expensive transfers involving an English club in history, resulting in a non-successful transfer [9]. So, in this way, Ćwikliński et al. [9] enrolled 4700 players from 156 clubs from one of the eight major leagues, and using technical ($n = 29$), psychological ($n = 7$), and match outcome ($n = 4$) features, they predict successful and non-successful player transferals, understanding success such as those transferals where the player's performance was up from the previous season and above the mean of his new team [9]. Lastly, and in agreement with the use of technical features, Sheng et al. [10] and García-Aliaga et al. [33] highlighted the potential use of ML to predict the most suitable playing position for a player [33], as well as predicting more suitable team tactics which may help coaches in decision-making [10] using both technical and positional features. So, technical features seem to be the most suitable inputs to predict talents in both young and professional soccer; however, and despite the large number of players involved in these studies, future studies are needed to highlight what are the most frequent contributors to predicting.

Study limits

Due to the unpredictable nature of soccer, the indications coming from ML should be considered with caution, taking into account that they may be only one piece of advice that can help coaches in decision-making in different ways.

Comparison of studies in this area is complicated nowadays for the following reasons:

- 1) Most of the selected studies use datasets created by the researchers themselves, which are not publicly accessible. This makes the published research not reproducible. Then, since ML models depend upon the quality and amount of dataset, authors may include them, at least, as a separate file in future research.
- 2) No studies have analyzed the amount of data input needed make to a relevant predictive attempt which makes accurate predicting available, further studies should analyze this issue.
- 3) Different data sources have been used in each article: subjective variables, biomechanical measurements, images or videos, mainly.

In any case, of all the articles selected in this review, and independently of the objective pursued, only 4 have used unsupervised algorithms [17-22-36-37], which indicates that better results are obtained for the applications analyzed with supervised algorithms.

CONCLUSIONS

Due to the development of technology, a large amount of data has become a widely used tool to manage training and competitions, using them to make decisions. Today, the development of algorithms capable of learning as more data are collected and stored has become known as ML in an important topic in soccer. Practically, the application of ML to soccer has been performed using a wide range of predictive algorithms, where those most considered are decision trees. Overall, three types of predictions can be made: (1) injury, (2) performance, and (3) talent predicting. (1) For injury prevention, pre-season screening, training load, genetics, or risk factor surveys (personal, psychological, and neuromuscular) can be used as inputs in a ML algorithm, where it may learn from the large amount of data added. (2) Performance predictive ML models were used in three ways: predicting outcomes, physical/physiological performance, and technical/tactical performance. While notational analysis and positional data can lead to predict match outcomes or even the final ranking of a league through ML, its approaches can help to identify the best contributors and determinants for explaining wellness and training load, and technical and tactical inputs can reveal passing effectiveness and classify team styles. (3) Finally, ML algorithms can lead to predicting a young talent, to predict a successful player's transferal between teams, and the player lineup most suitable for a competition, mainly using technical and positional data as inputs. Therefore, the use of ML may help team staff members in decision-making to predict dose-response relationships, reducing the chaotic nature of this team sport.

Publishing the datasets developed the authors could be a very good way of contributing to solving this lack of publicly available data and design comparative studies in the future.

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Conflicts of interest/Competing interests

The authors declare that they have no conflicts of interest relevant to the content of this systematic review.

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MRG led the project. MRG established the protocol, ran the data search and methodological assessment and wrote and revised the original manuscript. FMC wrote the original manuscript. JPO, AM and AB revised the original manuscript.

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Elite young soccer players have smaller inter-limb asymmetry and better body composition than non-elite players

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ABSTRACT: Body composition (BC) and inter-limb anthropometric asymmetries (LA) may influence the physical performance of soccer players. This study aimed to determine differences in BC and LA among soccer across four performance levels. The study involved 110 male soccer players participating in Czech senior teams who were grouped into four different performance levels (i.e. G1: national team, G2: 1st division, G3: 2nd division, G4: 3rd division). The following BC and LA parameters were compared among groups: body height, body mass, absolute fat-free mass, relative fat-free mass (FFMrel), percentage of fat mass (FM), total body water (TBW), intracellular water (ICW), extracellular water (ECW), phase angle, and bilateral muscle mass differences in the upper and lower extremities. Significant differences were observed in BC parameters among all groups ($\lambda = 0.06$, $F_{75,246} = 5.38$, $p = 0.01$, $\eta_p^2 = 0.62$). High-performance players (i.e. G1, G2) had significantly ($p < 0.01$) lower FM than lower performance players (i.e. G3, G4). The lowest values of FFMrel, relative TBW, relative ICW and ECW were detected in the lowest-performance players (i.e. G4). Significantly lower bilateral muscle mass differences were detected in G1 players ($2.71 \pm 1.26\%$; $p < 0.01$) compared with G4 players ($3.95 \pm 1.17\%$). G1 and G2 players had a higher proportion of muscle mass in the torso ($p < 0.01$) and upper limbs than G3 and G4 ($p < 0.01$). Elite and high-performance players have better BC and lower inter-limb anthropometric asymmetries compared with low-performance level players.

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INTRODUCTION

Elite soccer is a complex sport with a number of factors that may influence high performance, including technical and tactical skills, psychological factors, genetic predispositions [1] and physical fitness components [2] such as body composition (BC) [3]. Specifically, motor coordination and physical performance have been shown to discriminate between achievement level of soccer players [2, 4] within the meaning of current trends [5, 6, 7]. To achieve the highest sports performance and the opportunity to play in prestigious soccer competitions, players require long term preparation in specialized soccer programmes, mainly in talented youth development academies. About 16% of the academy players were promoted to the 1st or 2nd Spanish divisions in later years [6]. Although body size, muscle mass, maturation and physical performance (e.g. sprint, agility, endurance, jump test) have been found as limiting factors for career success in young soccer players [5, 8], no significant differences were found between players who remained members or left the academy. Conversely, no significant differences have been found within neuromuscular performance between successful and less

successful players of the Spanish league [6] and elite and amateur players of the French league [9]. After a continuous selection process in the elite soccer academies, Los Arcos and Martins [10] reported that promotion from the reserve team to high-level soccer is not determined by the improvement in physical fitness performance in older players (age = 20.5 ± 1.5 years). On the other hand, higher 20-m dash sprint speed was evaluated between senior national team, junior national team, 1st and 2nd division players, and 3rd–5th division, respectively [11]. Among above-mentioned physical characteristics, BC is an important mediator, which might provide desired differentiation between soccer performance levels.

Previous research reported that body fat mass (FM) is an important selection predictor for designated field positions (e.g. midfielders, defenders) and often distinguishes players who are highly or less successful [7, 12]. Elite players have a lower percentage of FM [13] and forwards are the leanest players among field positions [4]. On the other hand, no differences in FM were reported between professional and semi-professional Spanish players [14], particularly when

comparing their specific field positions (e.g. defenders, lateral defenders, central defenders, midfielders, lateral midfielders, central midfielders, attackers). Some studies have indicated that higher-level soccer players have significantly different BC compared with the rest of the players [4], although this finding is inconsistent and non-significant in other studies [2, 12], probably due to the different approach of performance level separation. There have been studies that compared FM and fat-free mass (FFM) among different levels of soccer players [12, 4].

Generally, soccer players who are taller, heavier, more muscular, and have higher FFM with lower FM may have major advantages, especially during the growth and maturation period [15]. A significant negative correlation was reported between FM and covered distance during sprinting in official matches [16], which indicates that players with lower FM are able to cover longer distances in sprints and high-intensity running during the match. Absolute FFM strongly contributes to strength and power performance, and is considered a major prerequisite for good performance in professional soccer players [17]. However, the relationships between FM and other BC variables and their role in the success of players of various performance levels, ages, and genders in team sports, along with other lower limb strength performance factors, remain unclear [18].

The BC assessment aimed to distinguish and quantify different body segments and their properties [19]. In soccer, cyclic and acyclic movements are combined at irregular intervals, and athletes may show a higher-than-normal degree of morphological and strength asymmetry [20]. Asymmetries are an adaptive consequence that is increased by long-term and intense sports activities [21], and can thus indirectly indicate the risk of injury to a soccer player, in which a lower form of morphological asymmetry determines the occurrence of functional asymmetry. Many studies of soccer have been conducted on various aspects. However, most of the studies have been based on elite-level soccer, and there is limited research comparing four different performance levels (i.e. top, elite, sub-elite, amateur) with different BC variables, such as intra- and extracellular water and phase angle, as well as focusing on the detection of morphological asymmetries.

Since body BC studies do not consistently report differentiating parameters, distinguishing performance levels, which provide more consistent differences than physical fitness parameters, and BC symmetry relates to the injury prediction, this study aimed to determine differences in BC parameters and morphological limb asymmetry among four performance levels in youth soccer player. We hypothesized that there would be substantial differences in BC among different performance levels of young players, and higher morphological asymmetries in favour of low-performance level players.

MATERIALS AND METHODS

Subjects

The study involved 110 male soccer players (age, < 17 years), who were divided into four groups according to the level of performance as follows: G1_{elite}, national team players (n = 20); G2_{elite}, 1st (highest) league players (n = 38); G3_{sub-elite}, 2nd league players (n = 32); and G4_{sub-elite}, 3rd division players (n = 20). The average period of soccer training experience for each group was 9.8 ± 3.6 years and typical training load during the week is shown in Table 1. The research was conducted from 2017 to 2020, during the pre-season player screening process. The basic anthropometric parameters of the players are included in the results (Table 2). The research design was approved by the Ethical Committee at Charles University, Faculty of Physical Education and Sport, and carried out according to the guidelines of the Declaration of Helsinki for human experimentation and the participants signed an informed consent form.

Data collection

Body height (BH) was measured using a digital stadiometer (Seca 242, Seca, Hamburg, Germany), and body mass (BM) was measured using a digital scale (Seca 769, Seca, Hamburg, Germany). Players were evaluated barefoot and wearing only undergarments. BC measurements were taken under the same conditions in the morning. In the 24 h prior to the measurement, the participants did not take any medications or pharmacological agents, including alcohol and caffeine, that may influence the results. They were also advised to abstain from food and fluids before the measurement, and

TABLE 1. Overview of a typical weekly training load (i.e. volume, frequency) for selected groups.

	G1_{elite} N = 20	G2_{elite} n = 38	G3_{sub-elite} n = 32	G4_{sub-elite} n = 20
Field-Based Training	5 (60–80 min)	5 (60–80 min)	4–5 (60–90 min)	3 (80–100 min)
Resistance Training	2 (UB, LB)	2 (UB, LB)	1 (WB)	Core (as a part of field session)
Match	1–2 (90 min)	1–2 (90 min)	1 (90 min)	1 (90 min)

Legend: UB = upper-body resistance session; LB = lower body resistance session; WB = whole-body resistance session; G1_{elite} = national team players; G2_{elite} = 1st division players; G3_{sub-elite} = 2nd division players; G4_{sub-elite} = 3rd division players.

TABLE 2. Basic anthropometric parameters of the players (N = 110).

Variables		G1 _{elite}	G2 _{elite}	G3 _{sub-elite}	G4 _{sub-elite}	ANOVA			Post-hoc test
		n = 20	n = 38	n = 32	n = 20	F	p	η_p^2	
Body height (cm)	X (SD)	178.66 (6.63)	179.34 (5.67)	178.75 (5.70)	180.91 (5.96)	0.67	0.58	0.02	
Body mass (kg)	X (SD)	71.74 (6.62)	70.83 (7.56)	67.37 (5.16)	74.46 (8.38)	4.56	0.01	0.11	G3 _{sub-elite} vs. G4 _{sub-elite}

Legend: G1_{elite} = national team players; G2_{elite} = 1st division players; G3_{sub-elite} = 2nd division players; G4_{sub-elite} = 3rd division players.

to maintain good hydration and a normal routine in the interim. Furthermore, the athletes did not perform any high-intensity physical activity for a significant duration in the 48 h before testing. The room temperature was maintained between 20°C and 24°C to prevent undesirable changes in body water composition [22]. BC was assessed using a multi-frequency bioimpedance analyser (MC-980MA; Tanita Corporation, Tokyo, Japan), according to the manufacturer's guidelines. Standardized conditions for bioimpedance measurements were maintained [23]. The BC indicators measured were as follows: BH, BM, FFM, relative fat-free mass (FFMrel), percentage of fat mass (FM), total body water (TBW), intracellular water (ICW), extracellular water (ECW), relative intracellular water (ICWrel), phase angle (PhA), muscle mass for the dominant and non-dominant lower limbs (MM_{DL} and MM_{NL}), muscle mass for the dominant and non-dominant upper limbs (MM_{DA} and MM_{NA}), and bilateral muscle mass (i.e. FFM) differences in the lower (Δ LE) and upper extremities (Δ UE). FFMrel was calculated as a normalized value of FFM to BM, and Δ LE, Δ UE were calculated as the percentage difference of the fat-free mass between the lower extremities.

Statistical analysis

The differences in selected BC parameters among the observed groups were assessed using multivariate analysis of variance. We used Levene's test for equality of variances to verify the homogeneity assumption that the variances of the dependent variable must be equal for all groups.

We used multiple comparisons of means (i.e. Bonferroni's post-hoc test) to compare differences in specific parameters among the groups. When the criterion of sphericity was not met as an assumption for data processing, as assessed by Mauchly's test (χ^2), the degrees of freedom were adjusted using Greenhouse-Geisser sphericity correction, and statistical significance was evaluated based on the degrees of freedom.

The level of statistical significance was set at $p < 0.05$. The effect size was assessed using the partial eta square coefficient (η_p^2), which was the basis for the categorization of effect size as follows: small effect, $\eta_p^2 = 0.02$; medium effect, $\eta_p^2 = 0.13$; and large effect, $\eta_p^2 = 0.26$.

The p-value indicating the probability of a type I error (alpha) was set at 0.05, in all statistical analyses. Statistical analyses were performed using IBM SPSS v24 (IBM, Armonk, NY, USA).

RESULTS

Multilevel analysis of variance revealed significant differences in BC parameters among all groups ($\lambda = 0.06$, $F_{75,246} = 5.38$, $p = 0.01$, $\eta_p^2 = 0.62$).

Anthropometric parameters

The results showed (Table 2) no BH differences among the analysed groups ($F_{3,106} = 0.67$, $p = 0.58$, $\eta_p^2 = 0.02$), but a significant effect ($F_{3,106} = 4.56$, $p = 0.01$, $\eta_p^2 = 0.59$) of performance level on body mass, where the BM in G3_{sub-elite} was significantly lower than in G4_{sub-elite}.

Body composition

The FM percentage was significantly different among the groups ($F_{3,106} = 50.10$, $p < 0.001$, $\eta_p^2 = 0.59$), where G1_{elite} and G2_{elite} groups had significantly lower values than the G3_{elite} and G4_{elite} groups (Table 3) and G3_{elite} had lower values than G4_{elite} (Table 3).

FFM was significantly ($F_{3,106} = 3.82$, $p = 0.01$, $\eta_p^2 = 0.10$) higher in G2_{elite} in comparison to G3_{sub-elite}, and FFMrel in G4_{sub-elite} group was significantly ($F_{3,106} = 14.35$, $p < 0.01$, $\eta_p^2 = 0.29$) lower than in the rest of the groups (Table 3).

Total body water (TBW) was not significantly different among the monitored groups ($F_{3,106} = 1.82$, $p = 0.15$, $\eta_p^2 = 0.05$). However, after comparing the TBW values according to body weight, the G4_{sub-elite} group had significantly ($F_{3,106} = 13.57$, $p = 0.01$, $\eta_p^2 = 0.28$) lower TBW values relative to body weight (TBWrel, %) than all other groups (Table 3). The body water components of ICW were higher (ICW: $F_{3,106} = 3.51$, $p = 0.02$, $\eta_p^2 = 0.09$) in the G2_{elite} group in comparison to the G4_{sub-elite} group (Table 3), and the G4_{sub-elite} group had lower ($F_{3,106} = 5.48$, $p < 0.01$, $\eta_p^2 = 0.13$) ICWrel (relative to ICW) values in comparison to the other groups at a higher performance level (Table 3). The ECW in the lowest performance group G4_{sub-elite} was significantly higher ($F_{3,106} = 10.64$, $p < 0.01$,

TABLE 3. Differences in body composition parameters among elite and sub-elite performance level groups.

Variables		G1 _{elite}	G2 _{elite}	G3 _{sub-elite}	G4 _{sub-elite}	ANOVA			Post-hoc test
		n = 20	n = 38	n = 32	n = 20	F	p	η_p^2	
FM (%)	X (SD)	9.92 (1.44)	9.50 (1.17)	13.47 (2.41)	17.04 (4.37)	50.09	< 0.01	0.59	G1 _{elite} vs. G3 _{sub-elite} , G4 _{sub-elite} G2 _{elite} vs. G3 _{sub-elite} , G4 _{sub-elite} , G3 _{sub-elite} vs. G4 _{sub-elite}
FFM (kg)	X (SD)	64.66 (5.13)	64.88 (5.79)	61.02 (5.78)	61.42 (5.58)	3.82	< 0.01	0.10	G2 _{elite} vs. G3 _{sub-elite}
FFMrel (%)	X (SD)	90.50 (2.24)	91.58 (4.37)	86.53 (6.89)	83.00 (4.70)	14.35	< 0.01	0.29	G4 _{sub-elite} vs. G1 _{elite} , G2 _{elite} , G3 _{sub-elite}
TBW (l)	X (SD)	45.59 (4.87)	46.17 (4.22)	43.95 (3.41)	44.83 (4.00)	1.82	0.15	0.05	
TBWrel (%)	X (SD)	63.54 (3.10)	65.30 (2.27)	65.33 (3.56)	60.44 (3.37)	13.57	< 0.01	0.28	G4 _{sub-elite} vs. G1 _{elite} , G2 _{elite} , G3 _{sub-elite}
ICW (l)	X (SD)	29.40 (3.74)	30.04 (3.26)	28.51 (4.53)	26.90 (2.40)	3.51	0.02	0.09	G2 _{elite} vs. G4 _{sub-elite}
ICWrel (%)	X (SD)	64.37 (1.61)	65.00 (2.38)	64.75 (3.72)	60.00 (3.24)	5.48	< 0.01	0.13	G4 _{sub-elite} vs. G1 _{elite} , G2 _{elite} , G3 _{sub-elite}
ECW (l)	X (SD)	16.19 (1.28)	16.13 (1.47)	15.87 (1.10)	17.93 (1.60)	10.66	< 0.01	0.23	G4 _{sub-elite} vs. G1 _{elite} , G2 _{elite} , G3 _{sub-elite}
PhA1 (°)	X (SD)	7.09 (0.56)	6.88 (0.51)	6.25 (0.67)	6.96 (0.72)	10.59	< 0.01	0.23	G3 _{sub-elite} vs. G1 _{elite} , G2 _{elite} , G4 _{sub-elite}
PhA2 (°)	X (SD)	7.13 (0.59)	6.80 (0.48)	6.24 (0.67)	6.72 (0.68)	10.83	< 0.01	0.24	G3 _{sub-elite} vs. G1 _{elite} , G2 _{elite} , G4 _{sub-elite}
PhA3 (°)	X (SD)	6.79 (0.42)	6.59 (0.48)	6.28 (0.42)	6.61 (0.43)	6.08	< 0.01	0.15	G3 _{sub-elite} vs. G1 _{elite} , G2 _{elite}
PhA4 (°)	X (SD)	6.77 (0.42)	6.53 (0.50)	6.22 (0.40)	6.56 (0.49)	6.80	< 0.01	0.16	G3 _{sub-elite} vs. G1 _{elite} , G2 _{elite}

Legend: FM = absolute value of fat mass; FFM = absolute value of fat-free mass; FFMrel = relative value of fat-free mass; TBW = total body water; TBWrel = relative value of total body water; ICW = intracellular water; ICWrel = relative value of intracellular water; ECW = extracellular fluid; PhA1 = phase angle right leg; PhA2 = phase angle left leg; PhA3 = phase angle right hand; PhA4 = phase angle left hand; G1_{elite} = national team players; G2_{elite} = 1st division players; G3_{sub-elite} = 2nd division players; G4_{sub-elite} = 3rd division players.

$\eta_p^2 = 0.23$) in comparison to other groups (Table 3).

The G3_{sub-elite} group had lower values of PhA1 ($F_{3,106} = 10.59$, $p < 0.01$, $\eta_p^2 = 0.23$) and PhA2 ($F_{3,106} = 10.83$, $p < 0.01$, $\eta_p^2 = 0.24$) than G1_{elite}, G2_{elite} and G4_{sub-elite} (Table 3); and lower values of PhA3 ($F_{3,106} = 6.08$, $p < 0.01$, $\eta_p^2 = 0.15$) and PhA4 ($F_{3,106} = 6.80$, $p < 0.01$, $\eta_p^2 = 0.16$) than G1_{elite} and G2_{elite} groups.

Segmental body fluid distribution

Analysis of the muscle mass volumes in the lower and upper limbs showed higher values ($p < 0.01$) of MM_{DL} and MM_{NL} between G2_{elite} vs. G3_{sub-elite} groups (Table 4), and lower values ($p = 0.02$) of Δ LE in G1_{elite} in comparison to G3_{sub-elite} group (Table 4). The G1_{elite} and G2_{elite} groups showed higher values of MM_{DA} ($p < 0.01$) and MM_{NA} ($p < 0.01$) in comparison to G3_{sub-elite}, G4_{sub-elite} groups

with no differences in Δ UE ($p = 0.43$) (Table 4). The trunk mass was lower in G3_{sub-elite} group in comparison to G1_{elite}, G2_{elite} groups (Table 4).

DISCUSSION

The analysis of basic anthropometric parameters did not reveal any difference in BH among performance groups, which agrees with the previous suggestion that BH may not be an individual criterion for career achievement, but it can be crucial in the selection for individual field positions [24]. According to Spanish league data, successful midfielders were taller and heavier than non-selected players [4] (selected: BH = 174.86 ± 6.98 cm, BW = 67.41 ± 8.19 kg; non-selected: BH = 170.45 ± 7.67 cm, BW = 62.10 ± 10.93 kg). This is contradicted by the Arnason et al. [2] study. Adult Iceland elite

TABLE 4. Comparison of segmental body fluid distribution among the elite and sub-elite performance groups.

Variables		G1 _{elite}	G2 _{elite}	G3 _{sub-elite}	G4 _{sub-elite}	ANOVA			Post-hoc test
		n = 20	n = 38	n = 32	n = 20	F	p	η_p^2	
MM _{DL} (kg)	X (SD)	10.81 (0.95)	11.00 (0.79)	10.24 (0.90)	10.47 (0.99)	4.68	< 0.01	0.12	G2 _{elite} vs. G3 _{sub-elite}
MM _{NL} (kg)	X (SD)	10.52 (1.02)	10.59 (0.87)	9.84 (0.90)	10.09 (1.00)	4.56	0.01	0.11	G2 _{elite} vs. G3 _{sub-elite}
ΔLE (%)	X (SD)	2.71 (1.26)	3.73 (1.70)	3.95 1.17	3.76 (1.50)	3.33	0.02	0.09	G1 _{elite} vs. G3 _{sub-elite}
MM _{DA} (kg)	X (SD)	3.54 (0.59)	3.78 (0.47)	2.98 (0.47)	2.96 (0.47)	20.85	< 0.01	0.37	G1 _{elite} vs. G3 _{sub-elite} , G4 _{sub-elite} G2 _{elite} vs. G3 _{sub-elite} , G4 _{sub-elite}
MM _{NA} (kg)	X (SD)	3.54 (0.57)	3.73 (0.48)	2.99 (0.46)	2.98 (0.45)	18.38	< 0.01	0.34	G1 _{elite} vs. G3 _{sub-elite} , G4 _{sub-elite} G2 _{elite} vs. G3 _{sub-elite} , G4 _{sub-elite}
ΔUE (%)	X (SD)	1.69 (1.88)	2.02 (1.94)	2.53 (2.32)	2.49 (1.95)	0.93	0.43	0.03	
Trunk (kg)	X (SD)	32.51 (2.80)	32.56 (3.07)	29.99 (2.49)	31.87 (2.77)	5.73	0.01	0.14	G3 _{sub-elite} vs. G1 _{elite} , G2 _{elite}

Legend: MM_{DL} = muscle mass of dominant lower limb; MM_{NL} = muscle mass of non-dominant lower limb; ΔLE = bilateral muscle mass difference of lower limbs; MM_{DA} = muscle mass of dominant upper limb; MM_{NA} = muscle mass of non-dominant upper limb; ΔUE = bilateral muscle mass difference of upper limbs; G1_{elite} = national team players; G2_{elite} = 1st division players; G3_{sub-elite} = 2nd division players; G4_{sub-elite} = 3rd division players.

division players were significantly taller than division I players, which might be related to the local population and study size conditions. We noted that our highest performance players (G1_{elite}) reached higher BH and BW (BH_{G1} = 178.66 ± 6.63 cm, BM_{G1} = 71.74 ± 6.62 kg) than the same age category players of the Belgian national team (176.8 ± 5.9 cm and 67.9 ± 6.7 kg, respectively) [25]. As the BH was not associated with the level of performance, the distinction is probably caused by the specific selection of the national team and individual extreme values at the time of evaluation.

Our study found that higher BM might be a performance disrupting factor, especially in combination with higher FM, ECW, and TBWrel, which was found in lower performance groups G3_{sub-elite} and G4_{sub-elite} (Table 3). This is in accordance with knowledge that soccer players with lower fat mass and higher lean mass may perform better than their lower-level peers in high-intensity intermittent running, change-of-direction speed, vertical jump, and sprint performance [26]. Several studies have investigated and confirmed negative correlations between increased fat mass and optimal muscle shortening, calcium signalling, physical performance, strength generation, sprint velocity, and aerobic power [16, 27 28, 29, 30, 31]. Although maintaining and developing active muscle mass and physical performance can potentiate higher anaerobic power output, systematically controlling and maintaining a lower FM does not increase excess BM. As a result, the muscles have a higher performance potential with a lighter resistance of the total BW [33].

FM does not seem to be a strict differentiating factor between elite levels, since we recorded no significant difference between the G1_{elite} and G2_{elite} groups [15, 34]. However, a significant difference in FM was observed between elite and sub-elite groups and between the G3_{sub-elite} and lowest performance group G4_{sub-elite} (Table 3). Our results are consistent with Reilly et al. [7], who reported higher FM in the sub-elite (13.9 ± 3.8%) than in elite soccer players (11.3 ± 13.9%) (age, 16.4 years; n = 31). Similarly, Gil et al. [4] reported significantly lower FM in selected players (11.43 ± 1.67%) than in non-selected players (12.56 ± 2.47%) for the defender position. However, no significant differences were observed among the different field positions (e.g. forwards, midfielders, and goalkeepers). These results may be due to the greater number of training hours per year in elite players (G1_{elite}, G2_{elite}) than in non-elite players. Vandendriesche et al. [25] reported that the youth Belgian national team (U17) had slightly higher FM (12.3 ± 3.0%) than our G1_{elite} and G2_{elite} groups (9.92 ± 1.44%). In adult players, there was no significant difference in FM between elite division players (9.9 ± 0.5%) and division I players (11.2 ± 0.5%) [2]. In addition, Rebelo et al. [34] reported no significant BC differences among elite (i.e. first division) vs. non-elite (i.e. regional division) Portuguese players in the under 19 years age category. Lower, although not significant, fat percentage was reported in successful teams than in unsuccessful young Spanish players (age, 15.63 ± 1.82 years) [12]. Male elite- and high-level soccer players typically undergo five to seven training sessions per week

with up to one to two games per week, whereas in low- to medium-level players reach half of these values (Table 1). Thus, elevated FM values, along with lower levels of muscle mass, may negatively affect physical performance in youth soccer players [35].

The values of muscle mass and total fat-free mass recorded in our study showed similar values in players with higher performance levels (i.e. G1_{elite} and G2_{elite}) and similar values in players with lower performance levels (i.e. G3 and G4). Figueireda *et al.* [32] reported a significant and positive correlation between the percentage of lean body mass and power performance (e.g. in the vertical jump) in professional players. Gil *et al.* [4] compared FFM values in successful (i.e. selected) and unsuccessful (i.e. non-selected) Spanish players (N = 231) at one level of competition, and found that, on muscle mass evaluation, there were no significant differences ($p > 0.05$) between the groups.

Monitoring the hydration status and body fluid volumes (i.e. TBW, ECW, and ICW) can help identify athletes who are at a higher risk of injury due to dehydration. Additionally, it can serve as the basis for prescribing fluid intake [36]. When estimating the distribution of fluids in terms of active muscle mass for individual body segments, the lowest bilateral morphological asymmetry was demonstrated in G1_{elite} players (< 3%), who had lower asymmetry than the G3_{sub-elite} group (Table 4). G2_{elite} players had a significantly higher volume of MM_{DL} and MM_{NL} than G3_{sub-elite} players. In connection with the non-significant difference in the basic anthropometric parameters, the obtained data imply a higher proportion of muscle mass in the lower limbs. The study findings also showed a higher proportion of upper limb muscle mass in the players from the G1_{elite} and G2_{elite} groups than in the players from the G3_{sub-elite} and G4_{sub-elite} groups. The proportion of torso muscle mass in the G1_{elite} and G2_{elite} groups was also higher than that in the G3_{sub-elite} group. This result points to the importance of optimizing muscle mass and strength as influential factors for player contacts and fights, successful ball coverage, heading duels, and overall physical demands in elite soccer.

The quality of BC in terms of predisposition to a higher-level performance was also confirmed by a significant difference in the directly measurable PhA parameters and the indirectly estimated ICW value, in which the lowest values were found in the G3_{sub-elite} group and the highest values were in the G1_{elite} group. The PhA values proportionally indicate muscularity in all players regardless of performance level and show the lateral preference of the kick leg. This difference was similarly observed in the upper limbs. Anaerobic performance measures showed that soccer players (age, 15 ± 1.4 years) with higher PhA values were faster in 10 m and 30 m sprints, and repeated sprint ability tests, and had higher ICW/ECW and TBW [37]. Independent of FFM, PhA has been shown to be positively correlated with maximum power and negatively correlated with the fatigue index [38]. In male soccer players, elite level players had significantly higher values of PhA and FFM than lower performance levels [39]. Some data suggest that

as long as the cell hydration remains uncompromised and the ICW/ECW profile is unaffected, the reduction of FFM will not destabilize PhA levels and performance [40]. As this directly measurable variable may effectively evaluate athletes' hydration status, cellular health, and physical function, there are limited recent studies which have reported on standard values for soccer athletes in different performance levels as well as research on PhA values among various sports [39, 41].

Mala *et al.* [15] reported the absence of morphological asymmetries in youth players (12–16 years old). In contrast, significant asymmetry was demonstrated in the elite players of the senior category, particularly goalkeepers, which was suggested to be due to unilateral limb preference in kicking and passing at greater distances during a game [42]. This hypothesis is also supported by Silvestre *et al.* [43], who recorded significantly lower FFM values in the dominant limb than in the non-dominant limb when comparing older players with younger players ($p < 0.05$). Focusing on asymmetry as a result of targeted and long-term sports activities, in which more experienced players tend to show greater asymmetries than less experienced players [44], muscle asymmetry and muscle strength can be attributed to unilateral preference in most one-sided soccer skills [45]. Morphological asymmetry is subsequently followed by functional asymmetry. Authors report that the occurrence of strength asymmetry and imbalance between flexors and extensors is associated with a higher risk of injury [20]. Players who have bilateral asymmetries greater than 15% are up to five times more prone to ischiocrural muscle injury than players who have lower asymmetry.

The effect of morphological asymmetry was also confirmed in the study by Mala *et al.* [15], in which the analysis between soccer players aged under 17 years and soccer players in senior categories revealed significant differences in the morphological symmetry of the lower limbs ($p < 0.01$). Emphasis was placed on increasing asymmetries with aging and on the need for early diagnosis and compensation for unilateral loading. Achieving an optimal BC and favourable anthropometric variables may be advantageous for young players not only in terms of gaining greater muscle strength and power, but also in developing more efficient movement [46].

The generalizability of these results is subject to certain limitations. For instance, the cross-sectional study design does not permit us to draw conclusions about the future success of the players, since players may improve later in consecutive study designs (e.g. longitudinal study). Moreover, we did not distinguish the subjects according to field positions, although anthropometric and morphological differences among various field positions have previously been reported by several studies [3]. Further investigations involving other age categories are necessary to predict and determine the level of future success of a soccer player. Another limitation is that we only controlled for chronological age. In future studies, it will be necessary to control for biological maturation, possibly using a bio-banding approach [47], and sexual maturation (i.e. Tanner stage).

CONCLUSIONS

The BC parameters and morphological asymmetries are related to the different performance levels, where high-performance players have high muscle mass in BC and lower bilateral asymmetry than low-performance players. Therefore, the training practice should emphasize high-quality and regular evaluations of BC, body hydration, and morphological asymmetry to enable early performance decrease, pathologic diagnosis and compensation for unilateral loading. Strength and conditioning or nutrition practitioners may also use the results of the present study to establish and create a tailored programme with the aim of achieving the most suitable anthropometric and BC profile for players at different performance levels.

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Conflict of interest

The authors declare no conflict of interest.

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Influence of anthropometric, ball impact and landing location parameters on serve velocity in elite tennis competition

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ABSTRACT: This study aimed (i) to analyse the associations between serve velocity (SV) and anthropometric, ball impact and landing location parameters in total serves (TS) and fastest serves (FS) performed during an ATP Tour event; (ii) to observe differences between first (S1) and second (S2) serves, and (iii) to determine a SV prediction model based on the relationship between the observed variables. Using Foxtenn technology, 30 S1 and 15 S2 were registered in 14 matches in twenty-one male professional tennis players. Ball impact (impact height [IH], impact projection angle [IPA] and relative impact height [RIH]), bounce landing (width and depth) location parameters, S1 and S2 SV in TS (TSV1 and TSV2) and FS (FSV1 and FSV2) alongside anthropometric characteristics of tennis players (body height [BH], body mass [BM] and body mass index [BMI]) were analysed. Significant moderate to large associations were found between BH and BM and TSV1, FSV1 and FSV2 ($r = 0.315$ to 0.593 ; $p < 0.001$), and between IH and IPA and TSV1 and TSV2 ($r = 0.294$ to -0.409 ; $p < 0.001$). BH and BM were the unique significant contributors of FS explaining 22 to 35% of FSV1 and FSV2. Only BM appears in the model to predict FSV1 and FSV2 ($r^2 = 0.48$ and 0.21). We concluded that all three anthropometric, ball impact and bounce landing location parameters small to moderately influence TSV. Anthropometric parameters show an impact on SV when tennis players serve at or near maximal speed, highlighting the influence of BM above BH.

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INTRODUCTION

Tennis serve (S) is a multifactorial nature stroke influenced by several neuromuscular, anthropometric, biomechanical, technical and tactical parameters. From a technical and biomechanical perspective, S has been considered as the most complex tennis stroke [1]. A broad consensus exists in considering that to apply an optimal force production, it is necessary to activate and coordinate multiple segments in the whole kinetic chain including lower limbs, trunk and upper limbs [2]. Specifically, it is necessary to add the forces from the ground up through the kinetic chain, to the upper limbs and finally to the racket [3], being necessary the use of elastic energy and muscle preload [4].

From a tactical and strategic perspective, a high S velocity (SV) and accuracy are a key factor in world-class modern tennis [5, 6]. SV has been considered the greatest contributor to S performance [7], and there is a significant relationship between SV and the probability of winning the point [6]. Nowadays, it is usual to see several SV up to $200 \text{ km} \cdot \text{h}^{-1}$, and although the Association of Professional Tennis Players (ATP) does not officially recognize SV records, a $263 \text{ km} \cdot \text{h}^{-1}$ S has previously been registered in a men's official

tennis match. In 2020, the top 10 ATP tennis players won $78.1 \pm 7.2\%$ of S games, there were 34 with up to an 80% and 3 players with up to 90% of S games won (<https://www.atptour.com/en>). The proportion of first S (S1) points won was significantly correlated with competition performance on all surfaces [8]. SV and accuracy determine decisive strategic aspects such as the percentage of points won on S, the number of S games won, or the number of points won directly or with short rallies (i.e., < 4 shots) [8]. This is especially relevant in males who get twice more aces per S game, win 14% more points on S1 and achieve 20% more unreturned S1 than female players [9]. Despite this, tennis performance is characterized by a complex interaction between physical, psychological, tactical, and technical abilities. When analyzing world-class athletes, different player profiles can be observed. Therefore, on which of the aforementioned aspects participants rely on more specifically to develop their game may vary significantly between individuals.

Given the importance of SV on success in professional male tennis competition, the recognition of factors that influence SV is currently relevant for researchers and coaches and therefore it has been

widely explored. The influence of different nature parameters of tennis players SV such as anthropometric characteristics [5, 10–12], competitive level [13], isometric [5, 14, 15] and dynamic [5, 10, 15–19] strength, rate of force development (RFD) [15], muscle stiffness [13], isokinetic speed [19], range of motion (ROM) [4, 16], lower and upper limbs joint kinematics and muscle activity [2, 11, 20–24], the match situation [25] or the resistance training [26] have been measured. However most of these investigations were conducted mainly in laboratory/court simulated conditions with absence of a returner [27]. Based on the uncertain nature of the game, tennis players constantly make decisions on ball landing location of their shots [6, 28]. It has been suggested that to appropriately register the S performance the representativeness of S and return is needed [29]. The S without a returner and real match conditions does not allow the server to decide direction, velocity and angle of S depending on the tactical situation.

Although modern technological advances allow to monitor and capture different performance parameters of strokes directly applying video-footage, there are few investigations carried out under real professional tennis events that reflect the influence of parameters related to the ball impact and bounce landing location. Furthermore, the influence of the anthropometric, ball impact and landing location parameters on total (TS) and fastest (FS) S performed during a real match have not been established. To the best of our knowledge, this is the first study that explores the influence of anthropometric, ball impact and bounce landing location parameters on first and second (S2) SV in total (TS) and fastest (FS) serves during an ATP competition, comparing differences between S1 and S2. Thus, the aims of the study were (a) to analyse the associations between SV and anthropometric, ball impact and landing location parameters in TSV and FSV in professional tennis players during an ATP Tour event; b) to observe differences between S1 and S2 and (c) to determine a SV prediction model based on the relationship between the observed variables.

MATERIALS AND METHODS

Participants

The inclusion criteria for the study were world-class male professional tennis players who participated in the singles main draw of the 2019 Barcelona Open Banc Sabadell and played in the central court of the tournament. The data of twenty-one male professional tennis players (mean $\pm$ SD; age, 26.4 ± 5.4 years; height, 186.9 ± 7.4 cm; BM, 81.6 ± 7.1 kg; body mass index [BMI], 23.4 ± 1.1 kg $\cdot$ m⁻²) were used for the performance analysis. The mean ATP ranking of the players was 42.2 ± 37.9 ranging from 2 to 155 and 81% were right-handed. Permission to use the data and the installations was granted by Reial Club de Tennis Barcelona · 1899. The study was performed in accordance with current ethical standards, established in the Declaration of Helsinki of the AMM (2013) and approved by the Clinical Research Ethics Committee of the Catalan Sports Administration (08_2020_CEICGC).

Experimental Design

The collection of data took place during an official ATP 500 outdoor red clay tournament (22–28 April 2019). The main draw of the tournament included a total of 48 elite tennis players of which 43.8% were analysed (<http://www.protennislive.com/posting/2019/425/mds.pdf>). For data analysis and in order to match the number of S evaluated in each player, the first 45 S per player (30 S1 and 15 S2) that landed in the service box (no foot fault or net cord) were registered in 14 matches between the second and fourth round, resulting in a total of 945 S (630 S1 and 315 S2) analysed. Data collection approximates to the professional S profile, the proportion of S1 and S2 in elite tennis are around 60 and 40% [8] and competition tennis players hit around 50 and 150 S during a match [30]. Matches were played approximately from 11 am to 20 pm. Parameters related to the ball impact point (impact height [IH], impact projection angle [IPA] and relative impact height [RIH]), ball bounce landing location (width and depth) and S1 and S2 velocities (SV1 and SV2) were registered for players in TS and FS. Moreover, anthropometric characteristics of professional tennis players (body height [BH], body mass [BM] and body mass index [BMI]) were registered. This procedure was used to determine to what extent anthropometric (BH, BM and BMI), ball impact (IH, IPA and RIH) and bounce landing location (depth and width) related to SV1 and SV2. On the other hand, multiple regression analyses were used to develop models that were most effective at predicting SV1 and SV2.

Measurements

Peak SV and ball impact and landing location parameters were recorded in real time by Foxtenn's technology (Foxtenn Bgreen, SL, Spain) currently used in ATP, WTA and ITF professional tennis events. Foxtenn's analysis technology system allows to capture ball trajectories through an automatic tracking of the ball that includes instantaneous ball position and ball velocities are also provided. Ball trajectories tracking is based on capturing images by multiple high-speed cameras of the real ball bounce in combination with high-frequency laser scanners fixed around the court (<https://www.itftennis.com/media/6215/pat-16-014-pat-approval-report-foxtenn-diamond-final-v0.pdf>). Specifically, the ball impact and bounce location parameters were determined by a high-speed camera (300 fps) positioned in the center of the baseline at a height of 8 m and 10 synchronized laser scanners (100 Hz each one) situated close to the ending lines at ground level and using as reference parameter the centre service line and the service line. Peak SV was determined using two radar guns (Stalker ATS II, United States, frequency: 34.7 GHz (Ka-Band) ± 50 MHz) positioned in the center of the baseline at a height of 2 m. The cameras, laser scanners and radar guns were wired to a server and a designated operator controlled the system via software running on a second server (connected to the first server). The system meets International Tennis Federation (ITF) criteria (<https://www.itftennis.com/media/7365/elc-evaluation-paper-revision-26.pdf>) of accuracy and reliability (<https://www.itftennis.com/media/7203/line-calling.pdf>) and is approved by

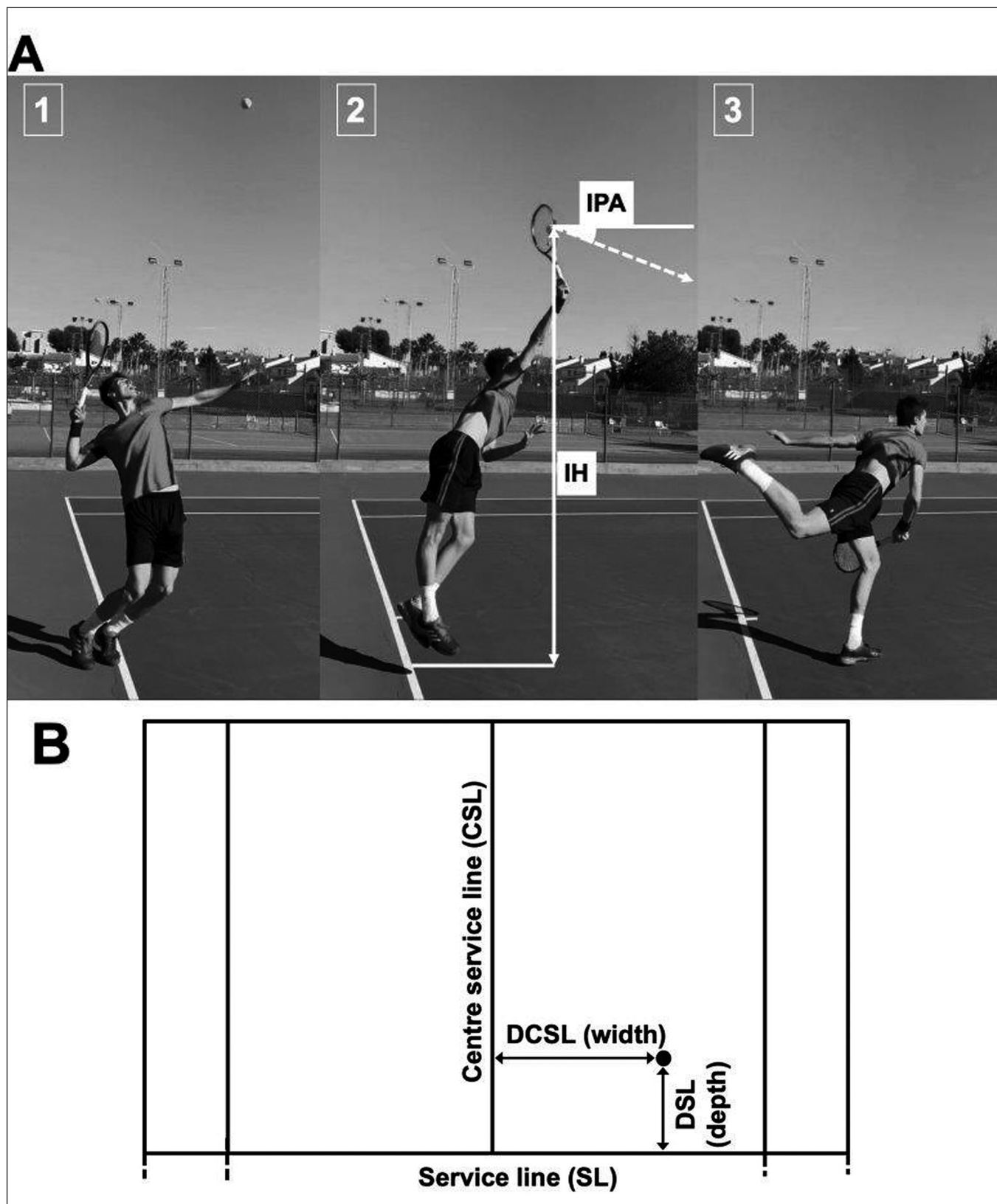


FIG. 1. Methods used to calculate ball impact (A) and landing location (B) parameters of tennis serve. Impact angle (IPA), impact height (IH), depth (distance to the service line; DSL) and width (distance to the centre service line, DCSL) are shown. Selected images of preparation phase (1, loading stage), acceleration phase (2, contact stage) and follow-through phase (3, finish stage).

the Women's Tennis Association (WTA) and ATP. Depth of service landing location was determined by the distance from the bounce to the service line (DSL) and width lateral bounce location by the distance from the centre service line (DCSL) (Figure 1B). IPA was determined by the ball impact projection angle from the horizontal (vertical projection angle) and IH by the distance in cm from the ball at the impact moment to the ground (Figure 1A). Figure 1A shows the three phases of specific serve model [1] and the ball impact parameters (IH and IPA) are located in the acceleration phase (second phase). Anthropometric characteristics of professional tennis players (BH and BM) were obtained from publicly available information listed in the official ATP website as in previous studies conducted in elite tennis players [12, 31]. RIH was determined by the relationship between IH and BH: $(IH/BH) \times 100$.

Statistical Analyses

Descriptive data are expressed as mean $\pm$ standard deviation (SD) and 95% confidence intervals (95% CI). The normality of variables distribution was assessed with the Shapiro-Wilk test. Most of parameters at TS1 (SV, IH, RIH and DCSL), TS2 (IH, RIH and IPA), FS1 (IPA and DCSL) and FS2 (RIH, IPA and DCSL) did not have a Gaussian distribution, so nonparametric test were used. Friedman's test was used to discern any significant differences between S1 and S2. Wilcoxon's test was used to identify those differences. Mean percent differences values were also used. The magnitude of the differences in mean was quantified as effect size (ES) and interpreted according to the criteria used by Cohen [32] < 0.2 = trivial, 0.2 – 0.4 = small, 0.5 – 0.7 = moderate, > 0.7 = large. Spearman rank order

correlation coefficients for non-parametric data were used to examine the relations between SV and anthropometric, ball impact and bounce variables, while coefficient of determination were used to explain the common variance between these variables and SV. Correlations were classified as trivial (0 – 0.1), small (0.1 – 0.3), moderate (0.3 – 0.5), large (0.5 – 0.7), very large (0.7 – 0.9), nearly perfect (0.9), and perfect (1.0) [33]. As DSL, and SV at FS1 and FS2 were normally distributed, parametric statistical analysis were conducted. Paired t-test was used to discern any significant differences between S1 and S2 and Pearson correlation coefficient was used to quantify the relationship between FS1, FS2 and DSL. TSV1, TSV2, FSV1 and FSV2 were used as the dependent variables in the stepwise multiple regression analysis, whereas anthropometric data (BH, BM, BMI) and ball impact variables (IH, IPA, RIH) operated as independent predictors. Ball landing location parameters (width and depth) were not used as independent predictors because it was considered that they depend on SV rather than the opposite. Statistical significance was accepted at an alpha level of $p \leq 0.05$. All statistical analyses were performed using IBM SPSS Statistics 26.0 (SPSS, Inc., Chicago, IL.).

RESULTS

TS1 and TS2 bounce landing locations are shown in Figure 2. TS2 and FS2 showed a large and a moderate to large reduction of SV ($ES = 1.30$ and 2.61 , -16.7 and -18.6% ; $p < 0.001$) and depth (increase in DSL: $ES = -0.63$ and -1.08 , 53.9 and 53.1% ; $p < 0.001$ and < 0.01) and a small to large increase in IPA ($ES = -0.42$ and -0.75 , 20.1% and 16.5% ; $p < 0.001$ and < 0.01) compared to the TS1 and FS1. No differences ($p > 0.05$) and small to trivial ES

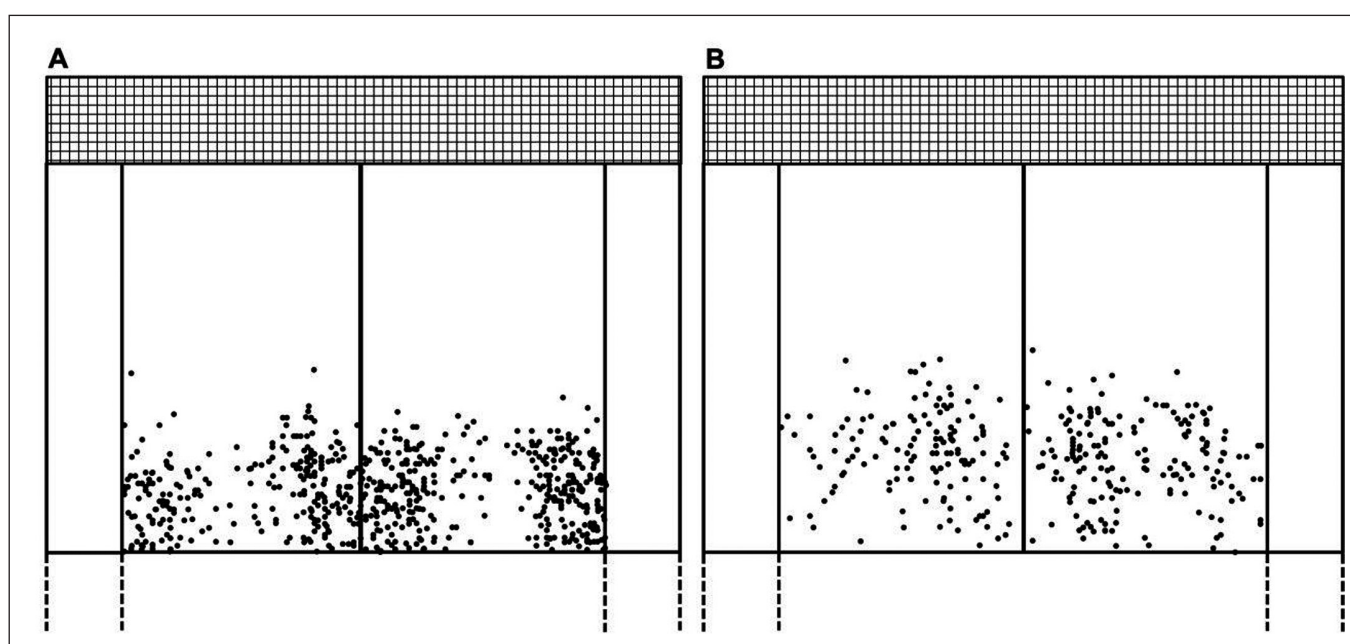


FIG. 2. First (A) and second (B) total serves (TS1 and TS2) bounce landing locations.

TABLE 1. Serve velocity (SV), impact (IH, IPA and RIH) and landing location (DCSL and DSL) parameters and differences between first and second total (TS1 and TS2) and fastest (FS1 and FS2) serves.

	TS (n = 945)							FS (n = 42)						
	TS1		TS2		Difference			FS1		FS2		Difference		
	(n = 630)	(n = 315)			p	ES	Descriptor	(n = 21)	(n = 21)			p	ES	Descriptor
SV (km · h ⁻¹)	173.6 ± 18.0 (172.4–175.1)	144.7 ± 13.1* (143.2–146.1)	< 0.001	1.30	Large	-16.7		201.3 ± 9.9 (196.8–205.8)	163.8 ± 9.2* (159.6–168.0)	< 0.001	2.61	Large	-18.6	
Ball impact location parameters														
IH (cm)	303.4 ± 11.9 (302.4–304.3)	303.3 ± 12.1 (302.0–304.7)	0.416	0.04	Trivial	-0.03		302.1 ± 11.3 (296.9–307.2)	304.3 ± 11.3 (299.1–309.4)	0.297	-0.25	Small	0.73	
RIH (%)	162.5 ± 2.2 (162.2–162.6)	162.4 ± 3.0 (162.0–162.7)	0.321	0.04	Trivial	-0.1		161.7 ± 2.3 (160.7–162.7)	163.0 ± 5.5 (160.5–165.5)	0.309	-0.27	Small	0.80	
IPA (°)	-4.37 ± 1.19 (-4.47– -4.29)	-3.49 ± 1.35* (-3.63– -3.34)	< 0.001	-0.42	Small	20.1		-4.62 ± 0.67 (-4.31– -4.57)	-3.86 ± 0.96* (-3.41– -4.30)	0.003	-0.75	Large	16.5	
Ball landing location parameters														
Width – DCSL (cm)	219.3 ± 138.0 (208.5–230.1)	209.1 ± 102.9 (197.7–220.5)	0.848	0.01	Trivial	-4.7		202.6 ± 149.0 (134.8–270.4)	155.9 ± 107.6 (106.0–204.9)	0.339	0.25	Small	-33.0	
Depth – DSL (cm)	101.6 ± 57.1 (97.2–106.1)	156.4 ± 73.7* (148.3–164.6)	< 0.001	-0.63	Moderate	53.9		70.8 ± 54.8 (45.8–95.8)	146.6 ± 62.5* (118.2–175.0)	< 0.001	-1.08	Large	53.1	

Data are mean ± SD (95% confidence interval). TS = total serves performed; TS1 = total first serves performed; TS2 = total second serves performed; FS = fastest serves; FS1 = fastest first serve; FS2 = fastest second serve; SV = serve velocity; IH = impact height; IPA = impact projection angle; RIH: relative impact height; DCSL = distance to the centre service line; DSL = distance to the service line; ES = effect size; Note: Magnitudes of ESs were assessed using the following criteria: < 0.2 = trivial, 0.2–0.4 = small, 0.5–0.7 = moderate, > 0.7 = large. *Significantly different from first serve.

TABLE 2. Correlation coefficients (r) between anthropometric (PH, BM and BMI), ball impact (IH, IPA and RIH) and landing location (DCSL and DSL) parameters and first and second total (TSV1 and TSV2) and fastest (FSV1 and FSV2) serves velocities.

	TSV (n = 945)						FSV (n = 42)					
	TSV1 (km · h ⁻¹)			TSV2 (km · h ⁻¹)			FSV1 (km · h ⁻¹)			FSV2 (km · h ⁻¹)		
	r	p	r ²	r	p	r ²	r	p	r ²	r	p	r ²
Anthropometric parameters												
BH (cm)	0.318	< 0.001	0.101	0.016	0.772	0.000	0.503	0.020	0.253	0.486	0.025	0.236
BM (kg)	0.315	< 0.001	0.099	0.075	0.186	0.006	0.593	0.005	0.352	0.466	0.033	0.217
BMI (kg · m ⁻²)	0.128	0.001	0.016	0.073	0.195	0.005	0.264	0.247	0.070	0.125	0.588	0.016
Ball impact location parameters												
IH (cm)	0.294	< 0.001	0.086	0.329	< 0.001	0.108	0.419	0.059	0.176	0.135	0.560	0.016
RIH (%)	-0.062	0.118	0.004	-0.050	0.379	0.003	-0.212	0.357	0.045	-0.397	0.075	0.158
IPA (°)	-0.391	< 0.001	0.153	-0.409	< 0.001	0.167	-0.177	0.443	0.031	-0.143	0.536	0.020
Ball bounce landing location parameters												
Width-DCSL (cm)	-0.173	< 0.001	0.030	-0.190	0.001	0.036	-0.127	0.585	0.016	0.039	0.867	0.001
Depth-DSL (cm)	-0.169	< 0.001	0.029	-0.179	0.001	0.032	-0.196	0.394	0.038	0.043	0.855	0.002

TSV = total performed serves velocity (all serves included); TSV1 = total first serve performed velocity; TSV2 = total second serves performed velocity; FSV = fastest serve velocity; FSV1 = fastest first serve velocity; FSV2 = fastest second serve velocity; BH = body height; BM = body mass; BMI = body mass index; IH = impact height; IPA = impact projection angle; RIH = relative impact height; DCSL = distance to the centre service line; DSL = distance to the service line; r = correlation coefficients; r² = determination coefficient.

TABLE 3. Anthropometric and ball impact variables included in the stepwise multiple regression analysis to explain the variance on first and second total (TSV1 and TSV2) and fastest (FSV1 and FSV2) serves velocities.

Dependent variables	Step	Independent variables entered	Correlations			SEE	p
			r	r ²	Adj. r ²		
TSV1 (n = 945)	1	BM	0.340	0.115	0.114	16.9	< 0.001
	2	BM and IPA	0.401	0.161	0.158	16.2	< 0.001
TSV2 (n = 315)	1	IPA	0.390	0.152	0.150	12.1	< 0.001
	2	IPA and IH	0.422	0.178	0.173	12.0	< 0.001
	3	IPA, IH and BH	0.441	0.194	0.187	11.9	< 0.001
	4	IPA, IH, BH and RIH	0.455	0.207	0.197	11.8	< 0.001
FSV1 (n = 21)	1	BM	0.712	0.506	0.480	7.1	< 0.001
FSV2 (n = 21)	1	BM	0.498	0.248	0.208	8.2	0.022

TSV1 = total first serves velocity; TSV2 = total second serves velocity; FSV1 = fastest first serve velocity; FSV2 = fastest second serve velocity; BM = body mass; IPA = impact projection angle; RIH = relative impact height; Adj. r² = adjusted coefficient of determination; SEE = standard error of estimate.

were found between IH, RIH and width at S1 compared to S2 (Table 1).

The correlation coefficients between the measured variables and TSV and FSV are presented in Table 2. Significant moderate and large positive correlations were found between anthropometric parameters (BH and BM) and TSV1, FSV1 and FSV2. The coefficient of determination between BH and BM and FSV1 and FSV2 ranged from 22 to 35%. Significant moderate positive (IH) and small to moderate negative (IPA, DCSL and DSL) correlations were found between ball impact and bounce landing location and TSV1 and TSV2. No significant correlations were found between ball impact and bounce landing location parameters and FSV.

Results of the stepwise multiple regression analysis to explore how the anthropometric and ball impact location values predicted the TSV and FSV are summarized in Table 3. BM and IPA analysed together explained 16% of the variation observed in the TSV1 (adj r² = 0.158; p < 0.001) and IPA, IH, BH and RIH explained 20% of the variation in the TSV2 (adj r² = 0.197; p < 0.001). Only the BM appeared in the predictive models of the FSV1 and FSV2 and explained 48 and 21% of the variation respectively (adj r² = 0.480 and 0.208; p < 0.001 and p = 0.022, respectively).

DISCUSSION

The main purpose of this study was to analyse the associations between SV and anthropometric, ball impact and landing location parameters in professional tennis players during an ATP Tour event and to observe differences between S1 and S2. Among the variables registered, anthropometric (greater BM and BH), ball impact (higher IH and IPA) and bounce landing (minor width and larger depth)

location parameters small to moderately influence TSV. However, the present findings reinforce the influence of anthropometric parameters (BH, BM) in SV when tennis player try to maximise ball velocity (i.e., TSV1, FSV1 and FSV2), but not when S are more conservative (i.e., TSV2). When tennis players serve at maximal SV (FSV1 and FSV2), the anthropometric parameters were the unique significant contributors of SV explaining 22 to 35% of SV. Moreover, the prediction model highlights the importance of BM above BH on FSV. S1 shows a large increase of SV in combination with moderate to large increases in depth and IPA compared to S2.

Regarding BH, it clearly seems that the tallest tennis players have a better disposition to serve fast, as its influence was large in FSV1 (r = 0.503), moderate on TSV1 and FSV2 (r = 0.318 and 0.486) and no influence was found in TSV2. This fact involves that as more powerful a S is, the influence of BH on SV is increased, emphasizing the importance of the principle of force production above the influence of longer connecting body segments. These results are somehow expected in agreement with studies registered in professional tennis tournaments such as the four Grand Slams (r = 0.31–0.57) [31] and Wimbledon (SV1, r = 0.640, p < 0.001) [11]. Greater BH allows a biomechanical benefit to SV over lower BH, as longer limbs allow to obtain higher peripheral head racket velocity at ball impact getting greater hand-racket angular momentum with the equal angular speed of upper body segments [15, 31, 34]. This association seems to be higher when S is tested in laboratory-court simulated conditions in professional tennis players for both S1 (r = 0.78, p < 0.05) and S2 (r = 0.80; p < 0.05) [10]. Possibly, the increase of the effect of BH in closed situations is because there is no decision making and decisive tactical factors of S performance involved

(i.e., depth, directions or accuracy). Players can focus only on SV execution, and this fact supports the hypothesis of the relevance to analyze the S influencing parameters during real competition.

In the same way as BH, BM demonstrated large associations with FSV1 ($r = 0.593$), moderate with TSV1 and FSV2 ($r = 0.315$ and 0.466) and no associations were found with TSV2. Moreover, BM explained 35% of the variability of FSV1. In line with this, moderate and large associations have been found in junior tennis players ($r = 0.44$ – 0.57 ; $r = 0.68$) [5, 15], but on the contrary, no associations have been found in S performed in a closed situation ($r = -0.22$ and -0.15 ; $p > 0.05$) [10]. Interestingly, the unique step in FSV1 (adj. $r^2 = 0.48$) and FSV2 (adj. $r^2 = 0.21$) and the first step in TSV1 (adj. $r^2 = 0.11$) included in the multiple regression analysis demonstrate the relevance of BM when players serve at or near maximal SV. The potential biomechanical factors that may cause the clear influence of BM on maximal SV are related to the principle of force (mass $\times$ acceleration) and torque production [5, 11]. Based on allometry assumption, BM is associated with torque production and an increased torque would reinforce SV [11]. In this sense, Gale-Wats & Nevill [35] established that the body structure (i.e., body composition) in world-class tennis players has been changing in recent times increasing their muscle mass and experiencing a transformation from endurance to power athletes. The same researchers suggested that a greater muscle mass and the ability to generate power production in all strokes in professional tennis players is associated with greater tennis performance, while taller but less muscled players (i.e., more linear body shape) would perform worse. However, although in professional tennis players we could assume that a high BMI is related to a greater muscle mass, we observed only a small influence of BMI in TSV1 ($r = 0.128$), but not in FSV. Contrary, in competition but not ATP level tennis players, BMI was largely associated ($r = 0.577$; $p < 0.05$) with SV [11] and moderate significant ($r = 0.32$ to 0.40 ; $p < 0.001$) and no significant ($r = 0.31$, $p > 0.05$) associations have been found in junior tennis players [5, 15]. Considering that BMI represents an interaction of two parameters (i.e., BM and BH), it is possible that a single increase in BM does not generate a significantly increase in SV and an optimal relationship probably exist between BM and BH to optimize SV.

Regarding ball impact location parameters (IH and IPA), they show a comparable influence to anthropometrics on TSV1 ($r = 0.294$ and -0.391), but contrary to BH and BM, a higher influence on TSV2 ($r = 0.329$ and -0.409) and no significant association with FSV. It seems that the benefit of ball impact location parameters on SV was lower when players try to maximize SV, however, we could speculate that they have a major impact on S accuracy. In addition to BH, there were diverse factors that could affect IH, such as vertical jump height, the vertical height of the hitting shoulder, the impact point on the string and the sum of arm and racquet length [7, 10, 31]. Also, it has been argued that IH could affect the precision of S. It has been stated that a higher IH contributes to a larger accessible

area in the service box [7] and allows a greater SV with the equal probability of the ball landing inside the service box [31]. RIH was introduced in the analysis as an IH and BH ratio, as it has been found that IH represents the 160% of BH showing the repercussion on IH of the factors that accompany BH (i.e., vertical jump height and vertical height of the hitting shoulder). RIH did not show any influence in SV, thus we could speculate that even if BH has a large influence on SV, the factors that accompany BH to determine IH does not affect SV. No differences in IH and RIH were found between S1 and S2, showing that these parameters are relatively stable in different tennis S (i.e., flat or topspin S). In this same line, no significant differences have been observed between S1 and S2 jump height [17]. It has been stated that in the S there is a higher biomechanical consistency of impact conditions than groundstrokes or volleys as a result of the initially stationary location on the court [27] and that players are able to dominate the main ball impact positions and to reproduce systematically the S performance [36].

Regarding IPA and in the same way that IH, a moderate influence on TSV was found, showing that a large IPA favours TSV but not FSV. However, moderate and large differences have been found between IPA in S1 and S2. In this same line, Chow et al. [37] observed greater IPA in the S1 than in S2 ($6.3 \pm 1.8^\circ$ vs $3.1 \pm 2.0^\circ$). We consider that IPA interpretation should be done alongside the analysis of depth (DSL) and ball velocity. The large differences found between S1 and S2 in depth ($\sim 50\%$) and ball velocity (~ 17 – 18%) together with the large differences in IPA (20 and 16.5%), shows that the S1 are significantly faster, deeper and with a major IPA than S2. Probably IPA may vary between flat and spin S and the less IPA and depth in S2 can be attributed to the slower SV and greater topspin. In S related with more speed and aggressive action (i.e., power S) players used flat S (i.e., minimum amount of spin on the ball) [22], contrary the S2 are conservative using topspin or slice which reduces SV [6]. A minor spin and higher SV are characterized by straighter ball trajectories over flight than slower S, and consequently, with a reduced clearance over the net to land in the service box. Contrary, on topspin S with greater ball spin rate and less ball velocity (i.e., S2) the Magnus force provokes further curved ball trajectory and lower forward velocity and depth [37, 38]. Therefore, the straight ball trajectory of fastest S needs a large IPA and allows it to reach a greater depth. From a tactical perspective, the greater SV and deeper landing location in S1 compared to S2 leads to a smaller margin of error, however it has been established that a greater SV offers a higher probability to win the S [39]. In agreement with this, the top 10 ATP tennis players until April 2020 won the $71.3 \pm 4.0\%$ of points played with the S1 and $49.7 \pm 7.2\%$ with S2 (<https://www.atptour.com/en>).

Visual inspection shows that S1 ball bounces (Figure 2A) are located closer to service centre line (i.e., T location) and singles sideline (wide location) and less into the centre service box (i.e., body location) than S2 (Figure 2B). Alongside a higher SV1 than SV2, the differences between S1 and S2 landing location probably occurs

because tennis players try to optimize the tactical advantage, number of aces or points directly won with S to a greater extent in the S1 than S2. In this same line, it has been shown that S1 are more effectively near to T location or near to the singles sideline (wide location) and body serves occur to a lesser extent [40]. Nevertheless, the negative moderate and small associations found between width and TSV1 and TSV2 ($r = -0.173$ and -0.190) shows a trend that fastest TS were closer to the centre service line (i.e., T location), especially in TSV1. An explanation for this could be that when players seek wide S, they tend to focus on accuracy of S to move the opponent off the court and achieve a positional advantage. Instead, when serving near the T location they seek to maximise S speed and diminish the time reaction of the opponent.

From a practical standpoint, our data emphasizes the influence of selected anthropometric (BM and BH) parameters on SV in professional tennis players during an ATP Tour event and reinforces the BM as an important influencing factor when players serve at or near maximal SV. In this regard, because BH can't be modified in adult tennis players, it can be postulated that neuromuscular strength training interventions aimed at increasing lean BM can be helpful for improving SV, especially in not very tall professional tennis players (i.e., < 185 cm). However, this assumption should be taken with caution since the ability to accelerate, decelerate and change of direction over short distances is paramount in tennis performance. A greater BM will produce a greater inertia demanding higher force production to produce a given change in velocity or direction [41], so an optimal interaction between increasing BM and COD performance should be found.

There are some limitations that need to be considered when interpreting the results of the present study. First, anthropometric characteristics of tennis players (i.e., BH and BM) were obtained from publicly available information listed in the official ATP website, assuming that the provided data may differ minimally from real data. Second, previously discussed, S is a highly complex stroke

determined by different nature parameters [1, 3], however the presented SV prediction model is based on a partial spectrum of serve performance (i.e., some anthropometric [BH and BM], ball impact and bounce variables). The model would be more accurate considering other determinant factors such as technical [39], strategic [6], range of motion [16, 24] or muscle power performance [5, 14–16] parameters.

CONCLUSIONS

In conclusion, the results of the present study have shown that anthropometric (greater BM and BH), ball impact (higher IH and IPA) and bounce landing (minor width and larger depth) location parameters small to moderately influence SV during an ATP Tour event. However, when tennis players serve at or near maximal SV, the influence of anthropometric parameters are increased being the major contributors to SV. The prediction model constructed highlights the influence of BM above BH on the fastest serves, suggesting its importance to generate power production at the professional tennis level. Moreover, S1 are deeper and show a greater IPA compared to the S2.

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Conflict of interest declaration

The authors declare that there is no conflict of interest between the participants, the materials and equipment used, or any other procedure undertaken during the experiments and the researchers of this investigation.

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Quantifying training load and intensity in elite male ice hockey according to game-related contextual variables

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ABSTRACT: We aimed to quantify training load (TL) and intensity during practice sessions according to game-related contextual variables (game outcome, opponent standard, game location) in an elite male ice hockey team. Practice data were collected using a wearable 200-Hz accelerometer, heart rate (HR) recording, and session-rating of perceived exertion (s-RPE) throughout 23 sessions ($n = 306$ files). The reference team performed a greater number of accelerations, decelerations, spent longer time $> 85\%$ maximum HR ($t85\%HR_{max}$) and reported greater s-RPE after losing a game compared to a win ($r = 0.13-0.19$). Moreover, a lower number of accelerations, decelerations, $t85\%HR_{max}$ and s-RPE ($r = 0.15-0.45$) were found before playing against a top-ranked opponent. In contrast, more accelerations, decelerations, longer $t85\%HR_{max}$ and greater s-RPE were observed after playing against a top-ranked team opponent ($r = 0.15-0.41$). The players performed more accelerations/min, spent more $t85\%HR_{max}$ and reported greater s-RPE before playing an away game ($r = 0.13-0.22$). Weekly TL seems to slightly increase after losing a game, when preparing a game against a weaker opponent, after playing against a stronger opponent, and when preparing an away game. On the other hand, training intensity seems not to be affected by game-related contextual variables. Thus, ice hockey practitioners involved with TL monitoring should consider the interplay of the numerous variables that influence the volume of prescribed training and the actual training responses in each individual player.

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INTRODUCTION

Training load (TL) monitoring, which has become a key area of attention of sports science support in contemporary team sports, aims to generate information concerning attainment of peak performance, to enable a certain level of protection against injury, and to provide an evidence-based and systematic approach to management of decisions when prescribing training [1]. In ice hockey, this is usually done using wearable technology embedding accelerometer and heart rate (HR) or collecting the rating of perceived exertion (RPE) during practice sessions and official games. However, limited attempts have been done to describe TL measures and intensity in elite ice hockey [2–5].

The external TL (ETL) describes the amount of physical work completed by the athlete. The ETL has recently been described in elite male [3, 2, 5] and female [4] ice hockey players using wearable technology. Beyond the relevant information available from ETL, different athletes may produce the same exercise output while experiencing different physiological and/or perceptual loading. In this context, the internal TL (ITL) is the individual athlete's response induced

by the ETL stimulus. ITL in ice hockey is usually determined using HR- and RPE-based parameters [2]. Recent findings have shown that the official game was the most demanding weekly session, and that day-to-day variations were more pronounced in HR- and RPE-based parameters rather than accelerations and decelerations [6]. Intense skating efforts performed during practice seem to be associated with that of competition, but not physiological and perceptual demands [6]. However, to our knowledge, no information has been reported regarding the influence of game-related variables (game outcome, opponent standard and game location) on TL and intensity in ice hockey.

Previous observational studies revealed that TL and intensity during the week can be affected by previous or upcoming game-related contextual factors in other team sports such as soccer [7–11], rugby union [12, 13] and basketball [14] showing controversial findings. For example, lower session-RPE (s-RPE; RPE $\times$ duration) has been reported after winning a game in U19 soccer [15] and semi-professional basketball players [14], or after losing a game in professional

rugby union [12]. On the other hand, greater total distance covered was found in the week after winning a game in elite soccer players [7]. Additionally, soccer players showed greater high-speed running ($> 16 \text{ km} \cdot \text{h}^{-1}$) when preparing a game against a weaker opponent (bottom five of the league rank [7]), whereas basketball players perceived greater s-RPE before facing a stronger opponent (first five of the league rank [14]). Furthermore, various team-sports players experienced different [15] or similar [7, 13, 11] TL when preparing an away or a home game. However, this information is yet to be explored in ice hockey. Therefore, the aim of this study was to quantify TL and intensity during practice sessions in elite Danish male ice hockey according to game-related contextual variables.

MATERIALS AND METHODS

Participants

17 elite Danish male ice hockey players (6 defensemen and 11 forwards; Mean $\pm$ standard deviation; age = 26 ± 5 yrs old, height = 181 ± 6 cm, body mass = 81.6 ± 6.9 kg, body fat = $13.6 \pm 2.2\%$ and $\text{HR}_{\text{max}} = 193 \pm 7$ bpm) competing at the highest Danish national level of play were regularly monitored in the context of their team practice sessions and game routines. Written informed consent was obtained from all the subjects. The Institutional Review Board of the University Southern Denmark approved the study, and written informed consent was obtained from all participants. The study adhered to the ethical code of the Declaration of Helsinki, and procedures were in line with established ethical standards in sports sciences [16].

Design

Practice sessions and competitive game data were collected using a wearable 200-Hz accelerometric system, HR and RPE throughout a four-week (29 days) competitive period, between February and March 2020. This was at the final stages of the regular season before a short break leading into the playoffs. Individual reconditioning sessions for injured players were excluded for analysis. Players participated in 23 practice sessions and 8 competitive games. Practice data included six sessions (92 files) on game-day minus 2, eight sessions (118 files) on game-day minus 1, and seven sessions (96 files) on game-day minus 0. Game-day minus 4 and 3 included one session (16 files) and as such were excluded from the study. The final sample comprised 306 practice sessions (median [range] = 18.5 [9–21] per player). To remove the effect of training frequency, TL and intensity data were expressed as average between game-day minus sessions as previously described [7]. The team won 4 games and loss 4 games and played 4 home and 4 away games. The opponent standard was classified as top (current 1st to 3rd of the rank), mid (4th to 6th team) and bottom (7th to 8th). During games, only players who spent a minimum of 4 min on the ice were considered [2]. No input was given about the research design to the technical staff throughout the data collection period. Data were collected in the context of the regular player' monitoring routine.

Procedures

The session-duration was regularly quantified by team' strength and conditioning coach. Acceleration and HR data were recorded using a wearable device incorporating a 200-Hz accelerometer and gyroscope (Polar Team Pro system, Polar, Kempele, Finland) and a 1-s interval telemetric system, respectively. The device (weight: 39 g; dimension: 36 mm $\times$ 68 $\times$ 13 mm) was placed on the lower sternum using an elastic band. Data were stored in the device and downloaded using the manufacturing software (POLAR Team Pro, Software version 1.3.1, POLAR, Polar Electro Oy, Kempele, Finland). Acceleration variables included the number of total accelerations (Acc_{tot}), total decelerations (Dec_{tot}), which both were expressed either in absolute values (number of efforts) and scaled by individual exposure time (efforts per min). The accelerometric system was tested for reliability by the study authors before the commencement of the study, and it provided comparable results to similar systems currently used in ice hockey (coefficient of variation ranging from 0.54 to 8.6%; [17]).

The HR indicators included time $> 85\% \text{HR}_{\text{max}}$ ($t85\text{HR}_{\text{max}}$) and mean HR (HR_{mean}), based on previous ice hockey studies [18, 2]. The players' HR_{max} was obtained in a previously described ice hockey specific incremental test [19].

The same strength and conditioning coach collected the player's individual RPE using Borg's category ratio scale after training sessions. Player RPE was collected in isolation to avoid the potential effects of peer pressure 15–30 min after each training session, ensuring that the perceived effort reflected the whole session and not the most recent exercise intensity [20, 21]. The overall TL was described by the session-RPE, which was calculated by multiplying the RPE score (0 to 10 AU) by the individual session' duration (in min, excluding games' warm-up) [22]. The validity of the s-RPE in ice hockey has been recently reported in relation to objective TL indicators ($r = 0.70\text{--}0.89$) [2].

Statistical analysis

Differences between game-related contextual factors were analyzed using a linear mixed model with unstructured covariance, taking into consideration the fact that the participants differed in respect of the number of training sessions in which they participated [23]. The specific contextual factor was set as fixed effect, individual subjects were set as random effects, and TL was the dependent variable. When a significant effect was found, pairwise comparisons were analyzed using a post-hoc Bonferroni test. The t statistic derived from the mixed model and from the paired sample' t test was converted to effect sizes' correlations [24] and qualitatively interpreted as: trivial ($r \leq 0.1$), small ($r = 0.1\text{--}0.3$), moderate ($r = 0.3\text{--}0.5$), large ($r = 0.5\text{--}0.7$), very large ($r = 0.7\text{--}0.9$) and almost perfect ($r \geq 0.9$) [25].

Descriptive statistics were presented as estimated marginal mean $\pm$ standard error. Statistical significance was set at $P \leq 0.05$. Data analyses were performed using Statistical Package for Social Science software (IBM SPSS Statistics for Windows, Version 26.0. Armonk, NY).

RESULTS

Playing position

Defensemen and forwards were exposed to similar training duration ($P = 0.589$). However, Defensemen were imposed slightly to moderately greater acceleration- and HR-based TL and intensity than forwards ($r = 0.23$ – 0.38 ; $P < 0.05$). No between-position differences were observed in s-RPE ($P = 0.867$). A detailed description of average TL and intensity in an elite Danish Ice Hockey team according to playing position is reported in Table 1.

Game outcome

No significant differences in TL and intensity were observed before a loss compared to a win ($P > 0.05$). However, players had slightly longer session-duration, performed a greater number of Acc_{tot}, Dec_{tot}, spent more t85%HR_{max} and reported greater s-RPE, after losing a game compared to a win ($r = 0.13$ – 0.19 ; $P < 0.05$). No significant differences were observed in training intensity after losing or winning a game (Acc_{tot}/min, Dec_{tot}/min, HR_{mean}; $P > 0.05$). A detailed

description of average TL and intensity in an elite Danish Ice Hockey team according to game outcome is reported in Table 2.

Opponent standard

Players were exposed to moderately lower training duration, performed less amount of Acc_{tot}, Dec_{tot} ($r = 0.37$ – 0.45 ; $P < 0.01$) and spent slightly lower t85%HR_{max} and reported lower s-RPE ($r = 0.15$ – 0.28 ; $P < 0.05$) before playing against a top-ranked opponent compared to mid- and bottom-ranked opponents. On the other hand, players were exposed to greater training duration, performed more Acc_{tot}, Dec_{tot} ($r = 0.18$ – 0.41 ; $P < 0.01$) and spent greater t85%HR_{max} ($r = 0.15$ – 0.32 ; $P < 0.05$) after playing against a top-ranked team compared to mid- and bottom-ranked opponents. Similarly, players reported greater s-RPE after playing against a top-ranked team compared to a mid-ranked team $r = 0.21$ [0.07–0.34]; $P = 0.002$). No significant differences were observed in training intensity according to the opponent standard (Acc_{tot}/min, Dec_{tot}/min, HR_{mean}; $P > 0.05$). A detailed description of average TL and intensity in an

TABLE 1. Average training load and intensity in an elite Danish Ice Hockey team according to playing position ($n = 306$ files).

Variable	Defensemen	Forwards	r (95 %CI)	P
Duration (min)	53.1 $\pm$ 1.6	54.2 $\pm$ 1.2	0.03 (-0.09; 0.15)	0.589
Acc _{tot} (count)	309.0 $\pm$ 9.1	264.1 $\pm$ 6.8	0.23 (0.12; 0.34)	< 0.001
Dec _{tot} (count)	307.2 $\pm$ 9.1	264.2 $\pm$ 6.8	0.22 (0.11; 0.33)	< 0.001
Acc _{tot} /min (count)	5.90 $\pm$ 0.08	4.86 $\pm$ 0.10	0.52 (0.43; 0.6)	< 0.001
Dec _{tot} /min (count)	5.86 $\pm$ 0.08	4.86 $\pm$ 0.10	0.52 (0.42; 0.6)	< 0.001
Time > 85%HR _{max} (min)	12.1 $\pm$ 0.7	6.1 $\pm$ 0.5	0.38 (0.27; 0.47)	< 0.001
HR _{mean} (%HR _{max})	73.7 $\pm$ 0.6	67.0 $\pm$ 0.4	0.49 (0.40; 0.58)	< 0.001
s-RPE (AU)	226.8 $\pm$ 12.7	224.1 $\pm$ 10.3	0.01 (-0.13; 0.15)	0.867

Acc_{tot}, total accelerations; AU, arbitrary units; CI, confidence intervals; Dec_{tot}, total decelerations; HR_{max}, maximum heart rate; s-RPE, session-rating of perceived exertion.

TABLE 2. Average training load and intensity in an elite Danish Ice Hockey team according to game outcome ($n = 306$ files).

Variable	Before				After			
	Loss	Win	r (95 %CI)	P	Loss	Win	r (95 %CI)	P
Duration (min)	52.9 $\pm$ 1.4	54.5 $\pm$ 1.3	0.05 (-0.07; 0.17)	0.418	56.3 $\pm$ 1.5	52.2 $\pm$ 1.2	0.13 (0.01; 0.24)	0.033
Acc _{tot} (count)	278.1 $\pm$ 8.5	281.7 $\pm$ 7.4	0.02 (-0.10; 0.14)	0.746	300.0 $\pm$ 8.7	266.6 $\pm$ 7.1	0.18 (0.06; 0.29)	0.003
Dec _{tot} (count)	278.1 $\pm$ 8.5	280.7 $\pm$ 7.4	0.01 (-0.11; 0.13)	0.823	299.5 $\pm$ 8.6	266 $\pm$ 7.1	0.18 (0.06; 0.29)	0.003
Acc _{tot} /min (count)	5.23 $\pm$ 0.09	5.24 $\pm$ 0.08	0.01 (-0.11; 0.13)	0.921	5.33 $\pm$ 0.09	5.17 $\pm$ 0.08	0.08 (-0.04; 0.20)	0.166
Dec _{tot} /min (count)	5.23 $\pm$ 0.09	5.20 $\pm$ 0.08	0.01 (-0.11; 0.13)	0.838	5.32 $\pm$ 0.09	5.15 $\pm$ 0.07	0.09 (-0.03; 0.21)	0.135
Time > 85%HR _{max} (min)	9.0 $\pm$ 0.7	7.7 $\pm$ 0.6	0.08 (-0.04; 0.20)	0.187	9.70 $\pm$ 0.70	7.3 $\pm$ 0.6	0.16 (0.04; 0.27)	0.009
HR _{mean} (%HR _{max})	70.3 $\pm$ 0.6	68.8 $\pm$ 0.5	0.11 (-0.01; 0.23)	0.058	70.3 $\pm$ 0.6	68.8 $\pm$ 0.5	0.11 (-0.01; 0.23)	0.062
s-RPE (AU)	235.9 $\pm$ 12.8	218.4 $\pm$ 10.1	0.08 (-0.06; 0.21)	0.287	250.7 $\pm$ 12.1	207.0 $\pm$ 10.2	0.19 (0.05; 0.32)	0.006

Acc_{tot}, total accelerations; AU, arbitrary units; CI, confidence intervals; Dec_{tot}, total decelerations; HR_{max}, maximum heart rate; s-RPE, session-rating of perceived exertion.

TABLE 3. Average training load and intensity in an elite Danish Ice Hockey team according to the opponent standard ($n = 306$ files).

Variable	Before				After			
	Bottom	Mid	Top	Pairwise comparisons	Bottom	Mid	Top	Pairwise comparisons
Duration (min)	58.8 ± 1.4	58.8 ± 1.4	41.9 ± 1.5	Bottom, Mid > Top	54.0 ± 1.3	45.1 ± 1.6	62.2 ± 1.6	Top > Bottom > Mid
Acc _{tot} (count)	312.0 ± 8.3	300.2 ± 8.6	217.7 ± 9.3	Bottom, Mid > Top	276.4 ± 7.9	239.9 ± 10	325.8 ± 9.9	Top > Bottom > Mid
Dec _{tot} (count)	311.2 ± 8.3	300.0 ± 8.6	217.1 ± 9.2	Bottom, Mid > Top	276.5 ± 7.9	237.4 ± 9.9	326.1 ± 9.8	Top > Bottom > Mid
Acc _{tot} /min (count)	5.36 ± 0.10	5.10 ± 0.11	5.23 ± 0.11	-	5.14 ± 0.09	5.33 ± 0.11	5.28 ± 0.11	-
Dec _{tot} /min (count)	5.33 ± 0.09	5.09 ± 0.10	5.21 ± 0.10	-	5.15 ± 0.08	5.27 ± 0.11	5.27 ± 0.11	-
Time > 85%HR _{max} (min)	9.2 ± 0.8	9.1 ± 0.8	6.1 ± 0.9	Bottom, Mid > Top	8.3 ± 0.7	6.2 ± 0.9	10.3 ± 0.9	Top > Bottom > Mid
HR _{mean} (%HR _{max})	69.4 ± 0.7	68.9 ± 0.7	70.1 ± 0.7	-	69.4 ± 0.6	68.7 ± 0.8	70.2 ± 0.8	-
s-RPE (AU)	236.3 ± 12.3	251.6 ± 12.6	168.7 ± 15.3	Bottom, Mid > Top	224 ± 11.3	188.9 ± 16.4	254.9 ± 14.3	Top > Mid

Acc_{tot}, total accelerations; AU, arbitrary units; CI, confidence intervals; Dec_{tot}, total decelerations; HR_{max}, maximum heart rate; s-RPE, session-rating of perceived exertion.

TABLE 4. Average training load and intensity in an elite Danish Ice Hockey team according to game location ($n = 306$ files).

Variable	Before				After			
	Away	Home	r (95 %CI)	P	Away	Home	r (95 %CI)	P
Duration (min)	57.2 ± 1.5	51.6 ± 1.2	0.18 (0.06; 0.29)	0.004	52.9 ± 1.7	54.3 ± 1.1	0.04 (-0.08; 0.16)	0.495
Acc _{tot} (count)	290.3 ± 8.9	273.6 ± 7.2	0.09 (-0.03; 0.2)	0.146	272.1 ± 10.0	283.8 ± 6.8	0.06 (-0.06; 0.18)	0.334
Dec _{tot} (count)	292.0 ± 8.9	271.6 ± 7.1	0.11 (-0.01; 0.22)	0.074	270.1 ± 9.9	283.9 ± 6.7	0.07 (-0.05; 0.19)	0.250
Acc _{tot} /min (count)	5.07 ± 0.09	5.34 ± 0.07	0.14 (0.02; 0.25)	0.025	5.20 ± 0.1	5.25 ± 0.07	0.02 (-0.1; 0.14)	0.725
Dec _{tot} /min (count)	5.08 ± 0.09	5.30 ± 0.07	0.11 (0; 0.23)	0.059	5.16 ± 0.1	5.24 ± 0.07	0.04 (-0.08; 0.15)	0.554
Time > 85%HR _{max} (min)	9.5 ± 0.7	7.4 ± 0.6	0.13 (0.01; 0.25)	0.031	7.3 ± 0.8	8.7 ± 0.6	0.08 (-0.03; 0.2)	0.163
HR _{mean} (%HR _{max})	69.8 ± 0.6	69.2 ± 0.5	0.04 (-0.08; 0.16)	0.503	68.7 ± 0.7	69.8 ± 0.5	0.08 (-0.04; 0.2)	0.197
s-RPE (AU)	259.1 ± 13.2	207.2 ± 9.6	0.22 (0.08; 0.35)	0.002	217.3 ± 13.6	229.3 ± 9.8	0.05 (-0.09; 0.19)	0.475

Acc_{tot}, total accelerations; AU, arbitrary units; CI, confidence intervals; Dec_{tot}, total decelerations; HR_{max}, maximum heart rate; s-RPE, session-rating of perceived exertion.

elite Danish Ice Hockey team according to the opponent standard is reported in Table 3.

Game location

Players were exposed to a slightly greater training duration, Acc_{tot}/min, t85%HR_{max} and reported greater s-RPE before an away game compared to a home game ($r = 0.13$ – 0.22 ; $P < 0.05$). No significant differences in TL and intensity were observed after a home or away game ($P > 0.05$). A detailed description of average TL and intensity in an elite Danish Ice Hockey team according to game location is reported in Table 4.

DISCUSSION

The main finding of this study was that weekly TL in a top-class Danish male ice hockey team seems to be affected by game-related contextual variables. Like other team sports, these effects appear

more evident in relation to the standard of the opponent and the results of the previous and following games rather than game location. Although greater training demands were imposed on defensemen compared to forwards, we found that players were exposed to (i) greater training volume after losing a game, (ii) lower TL when preparing a game against a stronger opponent, (iii) greater TL after playing against a stronger opponent and (iv) greater training duration, and acceleration frequency and cardiovascular loading when preparing an away game.

Our positional analysis revealed that although defensemen and forwards were exposed to similar training duration, defensemen were imposed slightly to moderately greater acceleration- and HR-based TL and intensity than forwards ($r = 0.23$ – 0.38). This contrasts with recent findings by Allard et al. [3] showing similar positional demands in on-ice load during practice sessions. However, our findings are similar to that observed in professional soccer, showing

greater weekly ETL demands in defenders compared to forwards [9]. However, based on the correlation between speed, acceleration and HR parameters in team sports games [26], the present results are partially supported by that of Lignell et al. [27] showing greater moderate ($14\text{--}17\text{ km}\cdot\text{h}^{-1}$) and fast ($17\text{--}21\text{ km}\cdot\text{h}^{-1}$) speed skating covered by defensemen during one official game. No between-position differences were observed in s-RPE, possibly suggesting that defensemen were better able to tolerate greater physical demands than forwards or that the work pattern may have differed (e.g., forwards accumulating their efforts in shorter bursts resulting in similar strain despite less absolute load). However, previous research has revealed similar on-ice change of direction, sprint and aerobic capacity between playing positions in elite ice hockey players [28, 29]. In this context, further studies are warranted to better elucidate positional differences in practice and match requirements in relation to fitness profiles. Alternatively, forwards may have performed a lower amount of brief intense actions leading to a lower HR kinetics compared to longer duration efforts observed in defensemen at a slightly lower intensity. A limitation in the comparison of playing position in ice hockey is that the forward lines are normally better represented than defensive pairings, which is also the case for the reference team in the present study. Thus, during specific team drills time on ice may reflect the game and be higher for defensemen than forwards.

The players in the present study were exposed to slightly longer session-duration, performed a greater number of accelerations and decelerations, as well as had higher heart rate loading and s-RPE, after losing a game compared to a win (see Table 2). This is supported by recent findings in elite soccer showing higher weekly total distance covered and high-speed running after losing a match [7, 8]. Moreover, our findings are partially supported by higher weekly s-RPE reported after a loss or draw compared to a win in U19 soccer [15] and semi-professional basketball [14]. On the other hand, our findings contrast with that observed in rugby union showing reduced s-RPE after a loss [12]. Additionally, no significant differences were observed in training intensity after losing or winning a game. Thus, the reason for the higher global TL after a loss may mainly be caused by longer sessions, potentially because coaches might be under pressure, but this does not appear to affect training intensity.

The investigated team was exposed to moderately lower training duration, performed a lower number of accelerations and decelerations, as well as experienced lower cardiovascular loading and reported lower s-RPE (Table 3) before playing against a top-ranked opponent compared to mid- and bottom-ranked opponents. This is in accordance with previous findings in basketball showing lower s-RPE before facing a top-level opponent [14], but in contrast to professional soccer [7] and rugby union [13] showing unclear differences in various TL variables before facing different opponents. The reduced training volume before playing against a stronger opponent could be attributed to the greater physical demands commonly observed in team sports, when competing against stronger opponents [30]. Indeed, coaches may reduce the volume of high-intensity activity in favor of tactical

preparation when preparing a game against top-level opponents simply to recover and avoid fatigue [31] while focusing on other components such as psychological preparation. This could possibly explain the higher rate of mechanical work when preparing for a game against a weaker team. Alternatively, increased work rate with stable physiological responses might indicate improved cardiorespiratory fitness and readiness to train and compete [32]. On the other hand, players were exposed to greater training duration and higher acceleration and deceleration count after playing against a top-ranked team compared to mid- and bottom-ranked opponents, which is supported by findings in professional soccer demonstrating increased total distance covered and high-speed running [7]. Additionally, cardiovascular loading and rating of perceived exertion were higher after playing against a top-ranked team, which contrasts with professional soccer [15, 7], basketball [14] and rugby union [13] observing trivial opponent effects on ITL. Although it is expected that coaches decrease the weekly TLs of starting players as a recovery strategy due to the opponent-induced match load, players might increase their work rate with a view to match selection. Collectively, it is difficult to draw conclusions about the cause-effect relationship between match-related contextual variables and changes in the volume of activity performed by the players.

In relation to game location players were exposed to a slightly greater training duration, acceleration frequency, cardiovascular taxation and s-RPE prior to an away game compared to a home game ($r = 0.13\text{--}0.22$). This contrasts with previous findings in soccer showing lower amount of high intensity accelerations in the week before an away game [7]. On the other hand, no significant differences in TL and intensity were observed after a home or away game, which is supported by previous findings in professional soccer [7], basketball [14] and rugby union [13]. This could result from players displaying residual fatigue after away games. Consequently, training intensity could have been reduced while maintaining training intensity because of cumulative loads over the previous days. On the other hand, given that sports teams normally alternate home and away matches, the volume of high-intensity activity was higher when preparing for an away game compared to a home game. This phenomenon could perhaps be explained by the possibility of improving recovery strategy (e.g., no travel) after home games and consequently increasing the weekly training stimulus.

It is important to note various limitations inherent in the present research, with the most important concerning the impossibility of obtaining a cause-effect relationship from observational studies. First, given the reduced sample size (e.g., team study) we have not accounted for the starting status. For instance, if the weekly TL was reduced for starting players, non-starting players might have experienced higher weekly TLs than advised. Future studies are therefore warranted to address the aforementioned concerns, taking into consideration that variations in TL are therefore likely to be, firstly, a direct function of coaching decisions and, secondly, of the actual short-term contextual variables of previous and following game [15].

In summary, this is the first study to quantify the weekly TL according to different game-related contextual variables using objective indicators derived from wearable technology embedding accelerometer and HR, as well a subjective indicator (s-RPE) in an elite ice hockey team. Our findings complement previous research investigating the effect of game-related contextual variables on TL and intensity in other team sports such as soccer [7–11], rugby union [12, 13] and basketball [14] and could be considered with caution by practitioners involved with TL monitoring in top-level ice hockey. The observed effect of game-related contextual variables on TL and intensity in the present study was of small to moderate magnitudes, underlining the need to identify further factors influencing weekly TL in professional male ice hockey.

CONCLUSIONS

Weekly TL seems to slightly vary (based on the magnitude of differences) according to the standard of the opponent, the location of a game, and the results of the previous game. Overall, TL

increased after losing a game, when preparing a game against a weaker opponent, after playing against a stronger opponent, and when preparing an away game. On other hand, training intensity was unaffected by game-related contextual variables. Thus, when planning training sessions, ice hockey coaches need to consider the interplay between the numerous variables that influence the volume of prescribed training (ETL) and the actual training responses (ITL) in each individual player. However, given the observational nature of the present study, future research is warranted to clarify cause-effect between game-related contextual variables and weekly TL.

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Contextualised high-intensity running profiles of elite football players with reference to general and specialised tactical roles

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ABSTRACT: The present study aimed to contextualise physical metrics with tactical actions according to general and specialised tactical roles. A total of 244 English Premier League players were analysed by coding player's physical-tactical actions via the fusion of tracking data and video. Data were analysed across 5 general (Central Defensive Players = CDP, Wide Defensive Players = WDP, Central Midfield Players = CMP, Wide Offensive Players = WOP, Central Offensive Players = COP) and 11 specialised positions (Centre Backs = CB, Full-Backs = FB, Wing-Backs = WB, Box-to-Box Midfielders = B2BM, Central Defensive Midfielders = CDM, Central Attacking Midfielders = CAM, Wide Midfielders = WM, Wide Forwards = WF, Centre Forwards = CF). COP covered more distance at high-intensity ($> 19.8 \text{ km} \cdot \text{h}^{-1}$) when performing actions such as 'Break into Box', 'Run in Behind/Penetrate', and 'Close Down/Press' than other positions (ES: 0.6–5.2, $P < 0.01$). WOP covered more high-intensity 'Run with Ball' distance (ES: 0.7–1.7, $P < 0.01$) whereas WDP performed more 'Over/Underlap' distance than other positions (ES: 0.9–1.4, $P < 0.01$). CDP and WDP covered more high-intensity 'Covering' distances than other positions (ES: 0.4–2.4, $P < 0.01$). Nonetheless, data demonstrated that implementing specialised positional analysis relative to a generalised approach is more sensitive in measuring physical-tactical performances of players with the latter over or underestimating the match demands of the players compared to the former. A contextualised analysis may assist coaches and practitioners when designing position or even player-specific training drills since the data provides unique physical-tactical trends across specialised roles.

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INTRODUCTION

As technology plays a more prominent role in modern football (soccer), the reliance on tracking-based technologies has increased exponentially [1]. Due to the complex nature of football, researchers have typically adopted a reductionist approach analysing either physical or technical metrics in isolation [2]. Despite this, a great deal of research has quantified the physical demands of elite players during matches and examined how this is affected by other factors such as positions, formations, and opponent standard [3–5]. Longitudinal match performance data trends emphasise that the distances covered at high-intensity have increased by ~20–30% with only a 2–4% increase in the total distance covered over the last decade [6, 7]. Consequently, greater attention has been paid to high-intensity actions as it helps practitioners to prepare players for the physical demands of modern match-play through benchmarking contemporary match-play requirements during training sessions [8].

High-intensity running profiles of various playing positions have been well documented [3, 9, 10] and used by coaches and practitioners to target modern football requirements that can be tailored according to different roles [11]. Nevertheless, the vast majority of studies in the scientific literature defined positional roles generically such as defenders, midfielders, and attackers [12, 13] or in terms of the general positions such as centre backs, full-backs, central midfielders, wide midfielders, and forwards [3, 10]. This generalised positional analysis limits our understanding of the true physical demands of players with more specialised tactical roles (e.g., central defensive or attacking midfielders) during a match [14]. Additionally, based on previous findings [10, 14, 15], one could assume that using a generalised positional analysis may be less sensitive in detecting the true physical-tactical match demands compared to a specialised positional method. Thus, research that compares general versus specialised positions is warranted to

identify whether disparities exist between the two different positional analyses.

Limited research has quantified the physical demands of elite players using a specialised playing position analysis. It has been reported that central attacking midfielders covered ~10–30% more high-intensity distance than central defensive midfielders [15, 16]. However, the methods of differentiating central midfield players into specialised roles in these studies were not disclosed, thus confounding study replication. Konefal and colleagues attempted to quantify performance profiles of specialised tactical roles using heat maps [17]. Yet, this study failed to differentiate full-backs (FB) and wing-backs (WB). Others have determined the tactical roles of wide defensive players (WDP) based on positions that are predefined within a playing system or formation [18, 19]. For instance, FB are based on a formation with four players at the back (e.g., 4-3-3 formations) and WB three at the back (e.g., 3-4-3 formations). The definitions of various wide defender subsets are not objectively defined but could relate to FB performing a more defensive role whilst WB could be regarded as a mixture of a FB and a winger due to dual responsibilities [8, 20]. Hence, differentiating player positions with specialised tactical roles should be accomplished by the observation of each player for the duration of match-play in addition to other analytical modalities (heat maps, average position etc.) to detect the true tactical role/playing style of players during match-play.

Although physical metrics provide some insight to practitioners, it is questionable how receptive coaches are to this basic data [2]. As coaches can sometimes have difficulty communicating with practitioners [11], especially in relation to data that are not contextualised appropriately. This seems to be due to researchers typically asking 'WHAT' distance players covered [2]. Therefore, analysing 'WHY' players cover that distance is very much warranted since the 'WHY' explains the modulators of the physical efforts. Recently, a systematic methodology that amalgamates physical metrics alongside their tactical purposes has been developed [21]. This approach may help coaches and practitioners understand the physical data contextualised to the tactical dynamics, thus allowing more practical application. Combining this approach with detailed specialised tactical roles would provide additional insights of individual's physical-tactical demands. Thus, the present study aimed to contextualise physical data with the key tactical purposes of the actions undertaken according to both their general and specialised tactical roles in which comparisons were made between them to determine their sensitivity in measuring physical-tactical performance during match-play.

MATERIALS AND METHODS

Match Analysis and Player Data

Match physical-tactical data were derived from the 2018–19 English Premier League season using an integrated approach and a novel filter developed for this research. Players' actions were captured by cameras placed at roof level during matches, and their physical-tactical actions were manually coded by using the

integrated approach. The validity and reliability of this approach have been previously verified and additional information regarding the data provider and filter used can also be found in this source [21]. The validity of the novel method demonstrated a strong agreement between the responses of both UEFA licensed coaches and performance analysts versus the gold standard responses (~92%), and its inter- and intra-observer reliability was a strong ($\kappa = 0.81$) to almost perfect ($\kappa = 0.94$), respectively. The new filter isolated high-intensity activities reaching speeds $> 19.8 \text{ km} \cdot \text{h}^{-1}$ for a minimal dwell time of 1 s [22].

The researcher completed 350 hours of coding to analyse 50 competitive matches. This consisted of the total number of 388 individual outfield players across 1,265 player observations. However, only outfield players who had completed the entire match in the same position were included (244 players across 583 player observations for the analyses of general positions). This consisted of Central Defensive Players (CDP, $n = 179$), Wide Defensive Players (WDP, $n = 147$), Central Midfield Players (CMP, $n = 167$), Wide Offensive Players (WOP, $n = 54$), and Central Offensive Players (COP, $n = 36$). However, for the analysis of specialised positions, 8 players were excluded since it was ambiguous to sub-categorise them into a specialised tactical role, thus this included 236 players across 529 player observations. This resulted in Centre Backs (CB², two at the back, $n = 130$; CB³, three at the back, $n = 49$), Full-Backs (FB, $n = 39$), Wing-Backs (WB, $n = 70$), Box-to-Box Midfielders (B2BM, $n = 94$), Central Defensive Midfielders (CDM, $n = 49$), Central Attacking Midfielders (CAM, $n = 11$), Wide Midfielders (WM, $n = 40$), Wide Forwards (WF, $n = 14$), and Centre Forwards (CF¹, one centre forward, $n = 14$; or CF², two centre forwards, $n = 22$). All data were analysed for the duration of each half, including stoppage time. Prior to analysis, all original data were anonymised to ensure confidentiality. Ethical approval was granted by Liverpool John Moores University (19/SPS/027) research ethics committee.

Match Control and Data Balance

Matches were randomly selected whilst simultaneously controlling various situational factors (phases of season, locations, and team or opponent standards) in line with previously outlined approaches [6]. Therefore, the number of matches for each factor was initially balanced. Matches were included only if they were close games (goal differential ≤ 2) and were excluded if there was a player dismissal as this can impact overall work-rates [23].

Demarcation of Player's Tactical Roles

A systematic approach was applied to the demarcation between various tactical roles using descriptors of general and specialised roles (Figure 1). The methodology of differentiating specialised positions was adapted from previous research [24]. Once outfield players were assigned to one of the five general positions (Figure 2A), they were then specifically sub-categorised according to their specific playing style/formation (Figure 2B). As various situational factors

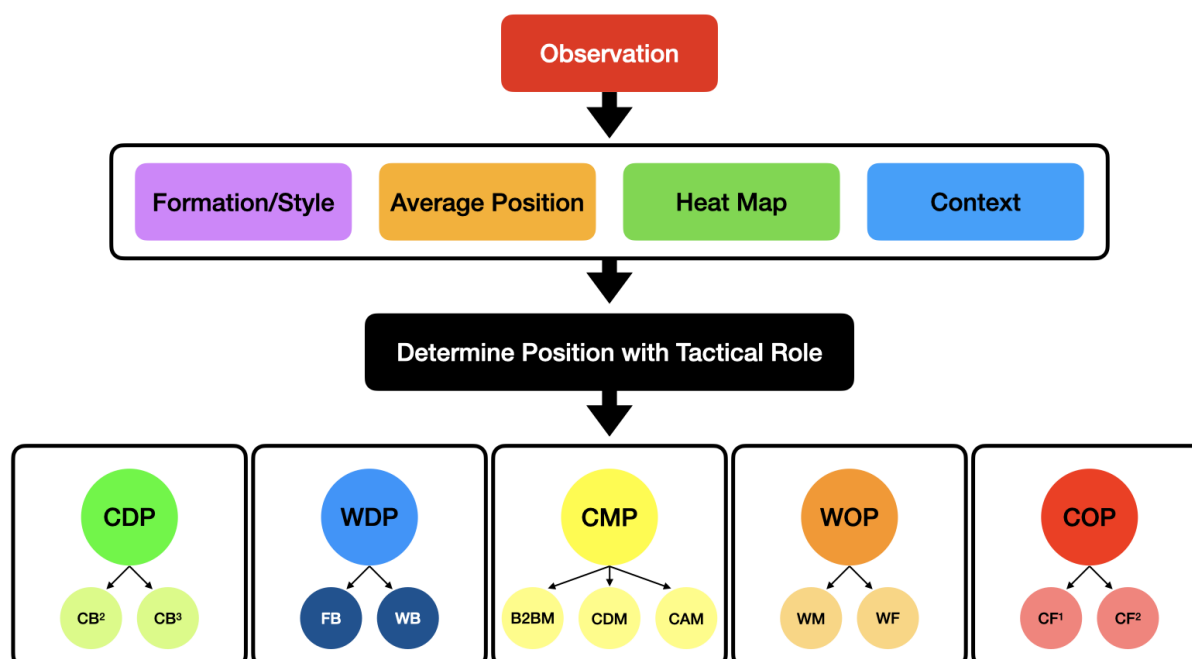


FIG. 1. The systematic process of determining a player's tactical role in the team. CDP: Central Defensive Players (CB2: two Centre Backs, CB3: three Centre Backs), WDP: Wide Defensive Players (FB: Full-backs, WB: Wing-backs), CMP: Central Midfield Players (B2BM: Box-to-Box Midfielders, CDM: Central Defensive Midfielders, CAM: Central Attacking Midfielders), WOP: Wide Offensive Players (WM: Wide Midfielders, WF: Wide Forwards), COP: Central Offensive Players (CF1: one Centre Forward, CF2: two Centre Forwards).

TABLE 1. Descriptions of the variables utilised within the integrated approach.

Variables	Description
In Possession	
Run with Ball	Player moves with the ball either dribbling with small touches or running at speed with the fewer ball touches.
Over/Underlap	Player runs from behind to in front of the player on the ball or receiving the ball.
Push up Pitch	Player moves up the pitch to play offside and/or to squeeze to a higher line.
Break into Box	Player enters the opposition's penalty box to receive the ball (typically receive ball from a cross – ball in front and wide).
Run in Behind /Penetrate	Player attacks space behind, overtakes and/or unbalances the opposition defence (typically ball is behind).
Move to Receive/ Exploit Space	Player moves to receive a pass from a teammate or to create/exploit space (typically come short or move wide to receive ball).
Support Play	Player supports from behind/level by trying to engage in offensive/transition play (typically during fast transitions).
Out of Possession	
Close Down /Press	Player runs directly towards opposition player on or receiving the ball, or towards space or players not on/ receiving the ball.
Interception	Player cuts out pass.
Recovery Run	Player runs back towards their own goal to be goal side when out of position.
Covering	Player moves to cover space or an opposition player while remaining goal side.
Unclassifiable	
Other	All other variables that could not be categorised by the above.

have an influence on the style of play that can be modulated by different tactical roles [25], context was considered whilst using a player's average position and heat map in an attempt to determine player's relevant tactical role in the team. This was verified by observing video footage of the entire match.

Inter-rater reliability for differentiating specialised tactical roles was assessed by two observers (UEFA qualified coach and the researcher) watching the entire match of players for each specialised tactical role ($n = 55$). The kappa statistic of 0.84 reflects a strong level of inter-observer consistency. Intra-observer reliability test undertaken

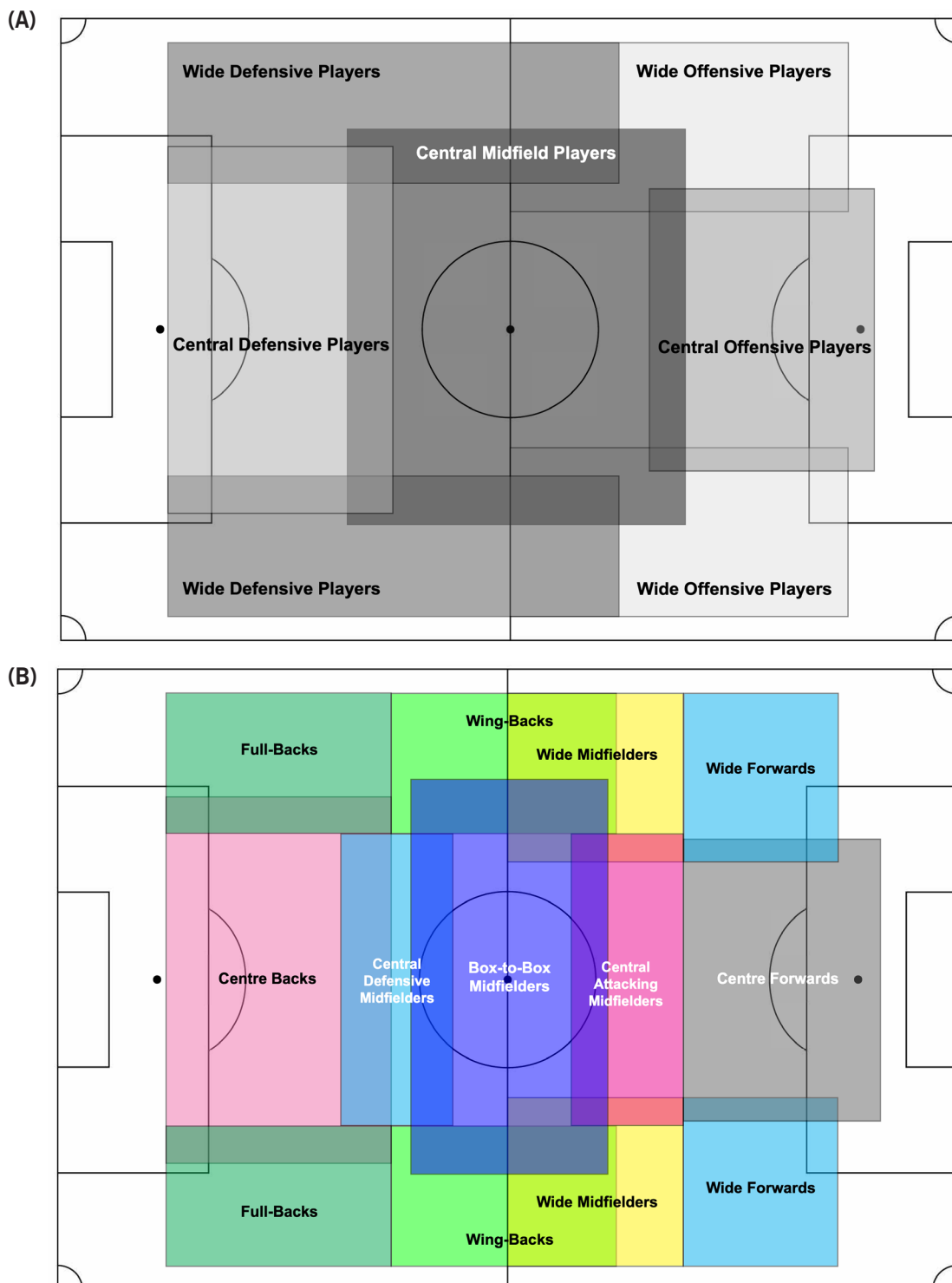


FIG. 2. General (A) and specialised (B) tactical roles based on match analyses. Adapted from Aalbers and Van Haaren [24].

by the researcher resulted in the kappa statistic value of 1.00, which is interpreted as a perfect intra-observer reliability [26].

The Integrated Approach of Match Performance

High-intensity actions isolated by the new filter were synchronised with video footage of each player throughout matches to code the tactical purpose of each action. All coding occurred using QuickTime Player (Apple Inc, Cupertino, California) to watch video and then categorise tactical actions (Table 1).

The coding process was as follows: high-intensity actions with one tactical action were classified as a single action with dual tactical actions being classified as a hybrid action. High-intensity actions with more than three tactical actions were coded as 'Other'. If the high-intensity action consists of 70–90% of the primary and 10–30% of the secondary action, it was classified as a hybrid action. However, if it is made up of 50–60% of the primary and 40–50% of the secondary action, then it was classified as 'Other'. As hybrid actions are a combination of the primary and the secondary actions [2], single action events and the primary tactical movements of the hybrid actions were merged to simplify data outputs.

Statistical Analyses

Data are presented as the mean $\pm$ standard deviation. All statistical analyses were conducted using IBM SPSS Statistics for Mac OS X, version 26 (IBM Corp., Armonk, N.Y., USA). Data normality was verified by Shapiro-Wilk and Kolmogorov-Smirnov tests. One-way

analyses of variance (ANOVA) were used to compare each position with Bonferroni post hoc test used to determine localised differences. Statistical significance was set at $P < 0.05$. Effect size (ES) for the meaningfulness of the difference was determined as follows: trivial (≤ 0.2), small (> 0.2 – 0.6), moderate (> 0.6 – 1.2), large (> 1.2 – 2.0) and very large (> 2.0 – 4.0) [27]. The coefficient of variation (CV) was analysed for match-to-match variabilities of general and specialised positions [28].

RESULTS

General Tactical Roles

In possession COP covered 62–1,434% and 88–32,767% more high-intensity distances for 'Break into Box' and 'Run in Behind/Penetrates' than other positions (ES: 0.6–2.8 and 1.1–5.2, respectively, $P < 0.01$) whilst WOP covered 71–323% more 'Run with Ball' distance than other positions (ES: 0.7–1.7, $P < 0.01$). WDP and WOP covered 35–8,254% and 38–748% greater high-intensity distances for 'Support Play' and 'Move to Receive/Exploit Space', respectively, than CDP and CMP (ES: 0.3–2.9, $P < 0.05$) with the former covering 548–5,340% more 'Over/Underlap' distance than other positions (ES: 0.9–1.4, $P < 0.01$).

Out of possession COP ran 89–2,307% greater high-intensity 'Close Down/Press' distance than other positions (ES: 1.1–4.2, $P < 0.01$). CDP and WDP performed 25–532% more high-intensity 'Covering' distance than other positions (ES: 0.4–2.4, $P < 0.01$) whilst WDP and CMP covered 34–670% more 'Recovery Run' than other positions (ES: 0.4–2.4, $P < 0.01$).

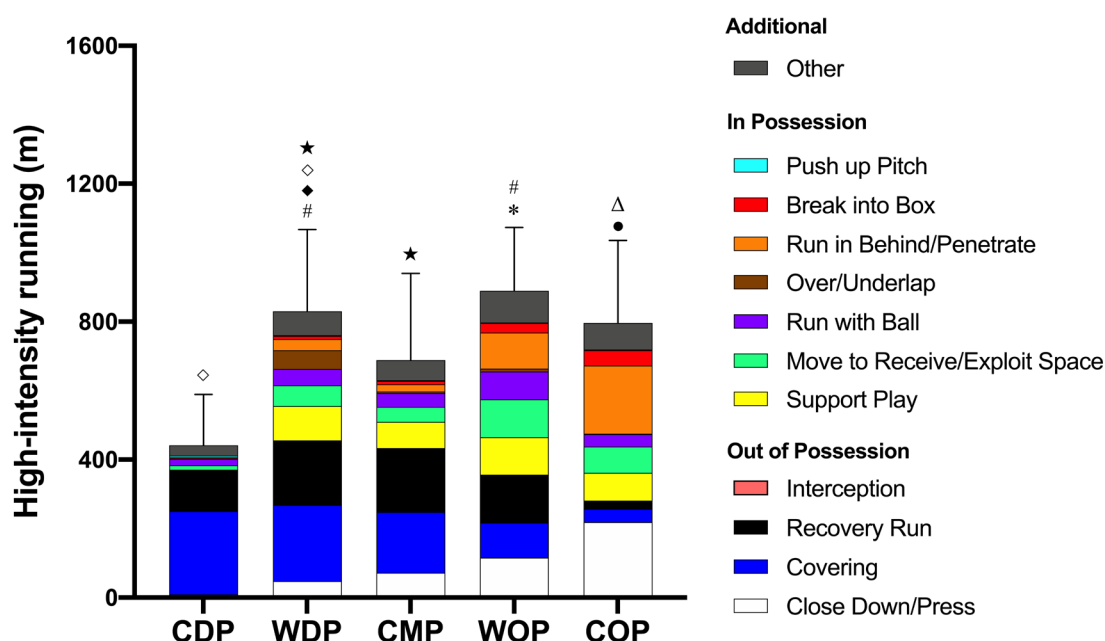


FIG. 3. Contextualised distances at high-intensity running covered by general positions. ★More distance for 'Break into Box' and 'Run in Behind/Penetrates' than others ($P < 0.01$). *More distance for 'Run with Ball' than others ($P < 0.01$). #More distance for 'Support Play' and 'Move to Receive/Exploit Space' than CDP and CMP ($P < 0.05$). ◇ More distance for 'Over/Underlap' than others ($P < 0.01$). ΔMore distance for 'Close Down/Press' than others ($P < 0.01$). •More distance for 'Covering' than CDP, WOP, and COP ($P < 0.01$). ★More distance for 'Recovery Run' than CDP, WOP, and COP ($P < 0.01$). 'Interception' and 'Push up Pitch' were very infrequent, thus not visualised on figure.

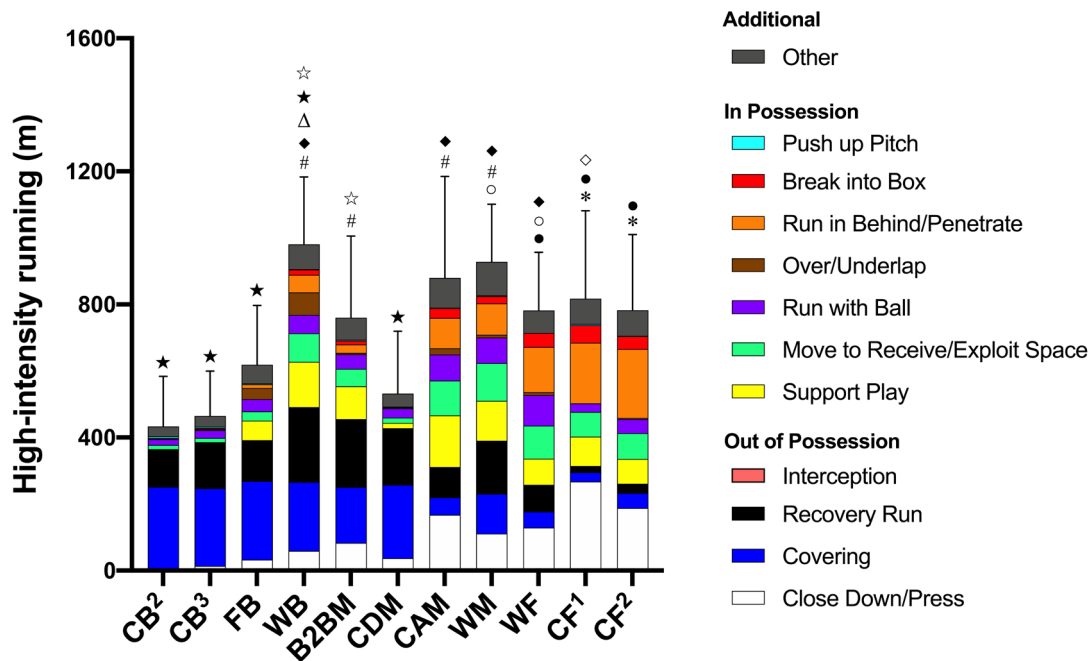


FIG. 4. Contextualised distances at high-intensity running covered by specialised positions. *More distance for 'Run in Behind/Penetrates' than CB², CB³, FB, WB, B2BM, CDM, and WM ($P < 0.01$). *More distance for 'Break into Box' than CB², CB³, FB, WB, B2BM, CDM, and WM ($P < 0.05$). °More distance for 'Run with Ball' than CB², CB³, FB, B2BM, CDM, CF¹ ($P < 0.01$). #More distance for 'Support Play' than CB², CB³, and CDM ($P < 0.01$). *More distance for 'Move to Exploit Space/Receive' than CB², CB³, FB, and CDM ($P < 0.01$). ^More distance for 'Over/Underlap' than others ($P < 0.01$). ◇More distance for 'Close Down/Press' than others ($P < 0.01$). *More distance for 'Covering' than CAM, WM, WF, CF¹, and CF² ($P < 0.01$). *More distance for 'Recovery Run' than CB², CB³, FB, CAM, WF, CF¹, and CF² ($P < 0.01$). 'Interception' and 'Push up Pitch' were very infrequent, thus not visualised on figure.

Run' distance than other positions (ES: 0.5–1.8, $P < 0.05$). Contextualised high-intensity distance for general positions are presented in Figure 3.

Specialised Tactical Roles

In possession, WB, B2BM, CAM, and WM covered 535–51,567% greater high-intensity 'Support Play' distance than CB², CB³ and CDM (ES: 1.0–5.0, $P < 0.01$). WB performed 103–16,925% more high-intensity 'Over/Underlap' distances than other positions (ES: 0.6–1.8, $P < 0.01$).

Out of possession, CF¹ performed 43–3,621% greater high-intensity 'Close Down/Press' distances than other positions (ES: 0.7–5.4, $P < 0.01$) while defensive players (CB², CB³, FB, WB, and CDM) covered 73–796% greater 'Covering' distance than offensive players (CAM, WM, WF, CF¹, and CF²; ES: 1.0–2.6, $P < 0.01$). Figure 4 illustrates contextualised high-intensity distance for specialised positions.

Comparison between Specialised Tactical Roles and their General Position

FB covered 34% less high-intensity distance (618 ± 178 m, ES: 0.9, $P < 0.01$) whilst WB covered 15% more distance (981 ± 203 m, ES: 0.7, $P < 0.01$) when compared to WDP (830 ± 238 m). CDM

covered 30% less distance in high-intensity running (532 ± 187 m, ES: 0.7, $P < 0.01$) whilst CAM performed 22% more distance than CMP albeit no statistical difference (880 ± 305 m vs 689 ± 251 m, respectively, $P > 0.05$). Table 2 depicts the average distance and duration per physical-tactical action with the average number of activities per match performed by general and specialised positions.

Match-to-Match Variability

The mean percentages of CVs for high-intensity distances produced by general and specialised positions were $22 \pm 13\%$ and $21 \pm 14\%$, respectively, whilst those for the contextualised actions were $67 \pm 25\%$ and $62 \pm 29\%$, respectively, regardless of physical-tactical variables.

DISCUSSION

The present study is the first to contextualise physical performance profiles of elite players with tactical activities executed across various tactical roles, whereby comparisons were made between general and specialised positions to determine disparities between them. Players' physical-tactical demands of play are significantly under or overestimated if adopting generalist positions (e.g., CMP, WDP and etc.), thus using a specialised positional analysis is critical to improving the sensitivity of player match performance. Data provides insights into 'WHY' players cover the high-intensity running distance during

TABLE 2. Average distance and duration per action with average number of actions per match across various tactical roles.

Type	Position	Variable	In Possession						Out of Possession			Overall
			SP	MTR/ES	OVL/UDL	RWB	RIB/PEN	BIB	CD/PRE	COV	RR	
General	CDP (n = 163)	Distance (m)	26 ± 19	18 ± 8	36 ± 11	17 ± 8	18 ± 6	14 ± 7	15 ± 5	18 ± 8	26 ± 15	20 ± 11
		Duration (sec)	3 ± 3	2 ± 1	4 ± 2	2 ± 1	2 ± 1	1 ± 1	1 ± 1	2 ± 1	3 ± 2	2 ± 1
		Actions (No.)	0 ± 0	1 ± 1	0 ± 0	1 ± 2	0 ± 0	0 ± 0	1 ± 1	13 ± 4	4 ± 3	23 ± 6
Specialised	CB ² (n = 130)	Distance (m)	28 ± 19	18 ± 8	26 ± 8	17 ± 7	16 ± 6	16 ± 9	15 ± 5	18 ± 8	27 ± 15	20 ± 11
		Duration (sec)	3 ± 3	2 ± 1	3 ± 1	2 ± 1	2 ± 1	2 ± 1	1 ± 1	2 ± 1	3 ± 2	2 ± 1
		Actions (No.)	0 ± 0	1 ± 1	0 ± 0	1 ± 2	0 ± 0	0 ± 0	0 ± 1	14 ± 4	4 ± 2	22 ± 7
	CB ³ (n = 49)	Distance (m)	13	17 ± 9	43 ± 6	19 ± 9	21 ± 6	12 ± 2	15 ± 5	19 ± 9	26 ± 14	20 ± 11
		Duration (sec)	1	2 ± 1	5 ± 1	2 ± 1	3 ± 1	1 ± 0	1 ± 1	2 ± 1	3 ± 2	2 ± 1
		Actions (No.)	0 ± 0	1 ± 1	0 ± 0	1 ± 2	0 ± 0	0 ± 1	1 ± 1	12 ± 4	5 ± 3	23 ± 6
General	WDP (n = 120)	Distance (m)	24 ± 13	20 ± 10	28 ± 14	22 ± 12	20 ± 9	19 ± 7	15 ± 5	20 ± 10	27 ± 14	22 ± 12
		Duration (sec)	3 ± 2	2 ± 1	3 ± 2	2 ± 2	2 ± 1	2 ± 1	1 ± 1	2 ± 1	3 ± 2	2 ± 2
		Actions (No.)	4 ± 3	3 ± 3	2 ± 2	2 ± 2	2 ± 2	0 ± 1	3 ± 2	11 ± 4	7 ± 4	38 ± 10
Specialised	FB (n = 39)	Distance (m)	22 ± 13	19 ± 8	28 ± 13	21 ± 12	21 ± 11	0	15 ± 5	20 ± 10	24 ± 12	21 ± 11
		Duration (sec)	2 ± 2	2 ± 1	3 ± 2	2 ± 2	2 ± 1	0	1 ± 1	2 ± 1	3 ± 2	2 ± 2
		Actions (No.)	3 ± 2*	1 ± 1*	1 ± 1	2 ± 1	1 ± 1*	0*	2 ± 2	12 ± 4	5 ± 3*	30 ± 7*
	WB (n = 70)	Distance (m)	25 ± 14	20 ± 11	28 ± 15	22 ± 12	20 ± 8	18 ± 7	15 ± 5	20 ± 10	27 ± 14	22 ± 12
		Duration (sec)	3 ± 2	2 ± 1	3 ± 2	2 ± 2	2 ± 1	2 ± 1	1 ± 1	2 ± 1	3 ± 2	2 ± 2
		Actions (No.)	5 ± 3****	4 ± 3****	2 ± 2	3 ± 2	3 ± 2****	1 ± 1***	4 ± 3	11 ± 4	8 ± 4	45 ± 8****
General	CMP (n = 132)	Distance (m)	23 ± 13	19 ± 9	22 ± 16	20 ± 10	20 ± 10	19 ± 10	16 ± 7	20 ± 10	24 ± 13	21 ± 11
		Duration (sec)	3 ± 2	2 ± 1	2 ± 2	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	3 ± 2	2 ± 2
		Actions (No.)	3 ± 4	2 ± 2	0 ± 1	2 ± 2	1 ± 2	1 ± 1	4 ± 4	9 ± 5	8 ± 4	34 ± 11
Specialised	B2BM (n = 94)	Distance (m)	23 ± 14	19 ± 10	21 ± 10	21 ± 10	21 ± 10	19 ± 10	16 ± 7	20 ± 10	25 ± 14	21 ± 12
		Duration (sec)	3 ± 2	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	3 ± 2	2 ± 2
		Actions (No.)	4 ± 4	3 ± 2	0 ± 1	2 ± 2	1 ± 1	1 ± 1	5 ± 3	9 ± 5	8 ± 4	37 ± 11
	CDM (n = 46)	Distance (m)	23 ± 13	16 ± 6	13 ± 3	19 ± 10	22 ± 4	28 ± 22	15 ± 6	20 ± 10	23 ± 12	20 ± 11
		Duration (sec)	3 ± 2	2 ± 1	1 ± 0	2 ± 1	3 ± 1	3 ± 3	1 ± 1	2 ± 1	3 ± 2	2 ± 2
		Actions (No.)	1 ± 1*	1 ± 1*	0 ± 0	1 ± 1	0 ± 0*	0 ± 0*	2 ± 0*	11 ± 5	7 ± 3	26 ± 8*
	CAM (n = 11)	Distance (m)	23 ± 11	19 ± 9	30 ± 27	23 ± 11	19 ± 9	17 ± 7	18 ± 8	20 ± 12	22 ± 13	20 ± 11
		Duration (sec)	3 ± 2	2 ± 1	3 ± 3	3 ± 2	2 ± 1	2 ± 1	2 ± 1	2 ± 2	3 ± 2	2 ± 1
		Actions (No.)	7 ± 4****	6 ± 3****	1 ± 1	3 ± 3	5 ± 4****	2 ± 1****	9 ± 8****	3 ± 2*	4 ± 2*	43 ± 14***
General	WOP (n = 40)	Distance (m)	23 ± 12	22 ± 12	21 ± 8	22 ± 12	21 ± 10	20 ± 8	18 ± 8	21 ± 10	24 ± 13	21 ± 11
		Duration (sec)	3 ± 2	2 ± 2	2 ± 1	2 ± 2	2 ± 1	2 ± 1	2 ± 1	2 ± 1	3 ± 2	2 ± 2
		Actions (No.)	5 ± 3	5 ± 3	0 ± 1	4 ± 2	5 ± 4	1 ± 1	7 ± 3	5 ± 3	6 ± 3	42 ± 7
Specialised	WM (n = 40)	Distance (m)	23 ± 12	22 ± 12	22 ± 8	23 ± 12	22 ± 11	19 ± 8	17 ± 8	21 ± 10	24 ± 13	22 ± 11
		Duration (sec)	3 ± 2	2 ± 2	2 ± 1	3 ± 2	2 ± 1	2 ± 1	2 ± 1	2 ± 1	3 ± 2	2 ± 2
		Actions (No.)	5 ± 3	5 ± 3	0 ± 1	3 ± 2	4 ± 4	1 ± 1	6 ± 3	6 ± 3	6 ± 3	44 ± 7
	WF (n = 14)	Distance (m)	22 ± 11	20 ± 10	18 ± 6	20 ± 10	19 ± 9	20 ± 9	19 ± 9	20 ± 9	24 ± 13	20 ± 10
		Duration (sec)	2 ± 2	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	3 ± 2	2 ± 1
		Actions (No.)	4 ± 2	5 ± 3	1 ± 1	5 ± 2	7 ± 4	2 ± 1	7 ± 4	2 ± 2*	3 ± 3	39 ± 7
General	COP (n = 23)	Distance (m)	29 ± 16	22 ± 11	24 ± 5	22 ± 11	21 ± 10	19 ± 7	20 ± 10	20 ± 9	25 ± 14	21 ± 11
		Duration (sec)	3 ± 2	2 ± 2	3 ± 1	2 ± 2	2 ± 1	2 ± 1	2 ± 1	2 ± 1	3 ± 2	2 ± 2
		Actions (No.)	3 ± 2	4 ± 3	0 ± 0	2 ± 2	9 ± 4	2 ± 2	11 ± 6	2 ± 2	1 ± 1	38 ± 10

TABLE 2. Continue.

Type	Position	Variable	In Possession						Out of Possession			Overall
			SP	MTR/ES	OVL/UDL	RWB	RIB/PEN	BIB	CD/PRE	COV	RR	
Specialised	CF ¹ (<i>n</i> = 14)	Distance (m)	29 ± 16	22 ± 11	0	25 ± 15	21 ± 9	19 ± 8	20 ± 11	19 ± 8	32 ± 11	21 ± 11
		Duration (sec)	3 ± 2	3 ± 2	0	3 ± 2	2 ± 1	2 ± 1	2 ± 2	2 ± 1	4 ± 2	2 ± 2
		Actions (No.)	3 ± 2	3 ± 2	0	1 ± 1	9 ± 3	3 ± 2	13 ± 7	1 ± 1	1 ± 1	38 ± 11
	CF ² (<i>n</i> = 22)	Distance (m)	29 ± 16	22 ± 12	24 ± 5	21 ± 10	22 ± 11	18 ± 7	19 ± 10	20 ± 9	23 ± 14	21 ± 11
		Duration (sec)	3 ± 2	2 ± 2	3 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	3 ± 2	2 ± 2
		Actions (No.)	3 ± 2	4 ± 3	0 ± 0	2 ± 2	10 ± 5	2 ± 1	10 ± 4	2 ± 3	1 ± 1	38 ± 9
General	Overall	Distance (m)	24 ± 14	20 ± 10	27 ± 14	21 ± 11	21 ± 10	19 ± 8	17 ± 8	19 ± 9	25 ± 14	21 ± 11
		Duration (sec)	3 ± 2	2 ± 1	3 ± 2	2 ± 2	2 ± 1	2 ± 1	2 ± 1	2 ± 1	3 ± 2	2 ± 2
		Actions (No.)	3 ± 3	2 ± 3	1 ± 1	2 ± 2	2 ± 3	1 ± 1	4 ± 4	10 ± 5	6 ± 4	33 ± 12
Specialised	Overall	Distance (m)	24 ± 14	20 ± 10	27 ± 14	21 ± 11	21 ± 10	18 ± 8	17 ± 8	19 ± 9	25 ± 15	21 ± 11
		Duration (sec)	3 ± 2	2 ± 1	3 ± 2	2 ± 2	2 ± 1	2 ± 1	2 ± 1	2 ± 1	3 ± 2	2 ± 2
		Actions (No.)	3 ± 3	2 ± 3	1 ± 1	2 ± 2	2 ± 3	1 ± 1	4 ± 4	10 ± 5	6 ± 4	32 ± 12

General Positions: CDP, Central Defensive player; WDP, Wide Defensive player; CMP, Central Midfield player; WOP, Wide Offensive player; COP, Central Offensive player. Specialised Positions: CB², two Centre Backs; CB³, three Centre Backs; FB, Full-backs; WB, Wing-backs; B2BM, Box-to-Box Midfielders; CDM, Central Defensive Midfielders; CAM, Central Attacking Midfielders; WM, Wide Midfielders; WF, Wide Forwards; CF¹, one Centre Forward; CF², two Centre Forwards. SP: 'Support Play', MTR/ES: 'Move to Receive/Exploit Space', OVL/UDL: 'Overlap/Underlap', RWB: 'Run with Ball', RIB/PEN: 'Run in Behind/Penetrate', BIB: 'Break into Box', CD/PRE: 'Close Down/Press', COV: 'Covering', RR: 'Recovery Run'. 'Push up Pitch' and 'Interception' were excluded as no differences were found between all positions. Values are means and standard deviations. *Less number of actions per match than their general position ($P < 0.01$). **Less number of actions per match than their general position ($P < 0.05$). ***Greater number of actions per match than their general position ($P < 0.05$). ****Greater number of actions per match than their general position ($P < 0.01$).

matches, which can ultimately help coaches and practitioners to design position- or even player-specific training drills. However, the reader should be aware that the match-to-match variability for high-intensity running distance (CV: 21–22%) and physical-tactical actions (CV: 62–67%) were high, which agrees with previous findings [29–32]. This could indicate that these context-based parameters are sensitive to the way teams set up tactically from game to game but also how each team modulates their own running performance and that of the opposition.

Previous studies demonstrated that the physical demand of match-play was highly dependent on playing positions with central defenders covering the lowest high-intensity running distance and wide midfielders the greatest [3, 10], which is in accordance with the findings of the present study. Interestingly, the studies above revealed that high-intensity running distance covered by wide midfielders (~1000–1200 m) was greater than that covered by wide defenders (~900–1000 m) although the present study demonstrated that there was no difference between WDP and WOP (~830 m vs ~890 m). Some discrepancies in the distance covered may occur between studies possibly due to different filtering methods and dwell times adopted [33]. That being said, it is more likely because the playing style of WDP has evolved from the traditional FB to WB in modern football, especially in the English Premier League where the

physical demands of match-play have increased significantly over the last decade [8]. This notion is further supported by the proportion in the sample of FB and WB in the present study (35% vs 65%, respectively). Nonetheless, without context it is difficult to draw firm conclusions regarding 'WHY' such demands have increased. The findings of the present study demonstrated that the increased physical demands of modern WDP (e.g., WB styles) appears to be due to them actively engaging in attacking and transition phases whilst performing high-intensity 'Support Play' and 'Over/Underlap' activities when in possession, and 'Recovery Run' actions when dispossessed (i.e., out of possession), which is consistent with previous findings [20, 29]. This particular trend of WDP in modern European football may exist as a function of tactical evolution [20], and depends upon a team's philosophy/tactics (e.g., how the team use WDP during a match). Therefore, applied staff should consider the playing style of their WDP within the team (e.g., FB or WB) when prescribing training drills that are tailored to the players given the substantial differences in the physical-tactical demands between them. Additionally, as the integrated approach is sensitive enough to detect specific playing styles of players with their unique physical-tactical attributes, this has some potential benefits for recruitment. For instance, players who have the physical-tactical attributes matched to the team's playing style could be shortlisted for scouting. However,

to be able to build team and positional-level physical-tactical profiles, recruitment teams need to be able to use the same level of detail presented in this study to recruit players that possess the physical qualities to execute the team's desired tactical plan.

Unlike previous research that analysed physical metrics in isolation [4, 10], the present study demonstrated unique physical-tactical match profiles inherent in various tactical roles. In possession, COP covered more high-intensity distance for 'Break into Box' (ES: 0.6–2.8) and 'Run in Behind/Penetrate' (ES: 1.1–5.2) compared to other positions. This could be explained by offensive players attacking space in behind the opponent back line and/or entering the box to score a goal [34]. Additionally, WOP performed greater 'Run with Ball' distance at high-intensity (ES: 0.8–1.7) whilst WDP ran more 'Over/Underlap' distances (ES: 0.9–1.4) compared to other positions, both of which agree with previous findings [29, 35]. Furthermore, WDP and WOP performed more high-intensity distance for 'Support Play' (ES: 0.3–2.9) and 'Move to Receive/Exploit Space' (ES: 0.3–2.5) than CDP and CMP. It is noteworthy in that CMP covered less distance at high-intensity for 'Support Play' than WDP and WOP given the purpose of the action. 'Support Play' is when the ball is played forward quickly and the players behind or level with the ball tend to produce high-intensity efforts to become involved in the attacking/transition phase of play, which is vital to produce an offensive threat [36]. This disparity may be due to a variety of tactical roles within CMP (e.g., B2BM, CDM and CAM) in which the highest percentage spread in high-intensity running distance (32–33%) has been reported [7]. Furthermore, this could be explained with the data for specialised tactical roles, demonstrating that no differences were observed in the high-intensity distance covered for 'Support Play' between B2BM, CAM, WB, and WM, but all of them covered ~670–890% greater distance than CDM.

Out of possession, COP performed more high-intensity 'Close Down/Press' activities than other positions (ES: 1.1–4.2). This may be due to the increased adoption in modern football of the 'pressing' tactic. [37]. Nonetheless, when it comes to specialised tactical roles, CF¹ covered ~40% greater high-intensity distance for such actions compared to CF² (~270 m vs ~190 m, respectively). This is possibly be due to the number of players up front as forwards since a single centre forward (e.g., forwards in a 4-5-1 formation) tends to cover greater high-intensity distance when out of possession [5] compared to two players up front (e.g., forwards in a 4-4-2 formation). In contrast, CDP covered less distance at high-intensity for 'Close Down/Press' but greater for 'Covering' compared to other positions. This might be because CDP have limited space to achieve high-intensity running ($> 19.8 \text{ km} \cdot \text{h}^{-1}$) to close the opponent down when defending but have more space behind them to cover space or a player whilst being goal side, especially when they are around the half line [19]. This could be confirmed by the fact that the average high-intensity distance covered by CDP for 'Closing Down/Press' was lower than COP (~15 m vs ~20 m, respectively). CDP may accelerate more to close down the opponent since maximal accelerations are often

executed at velocities below high-intensity speed thresholds [38]. This suggests that the ability to frequently perform accelerations is a key requirement for CDP to be prepared for. Collectively, physical-tactical performance data clearly explains 'WHY' players cover the high-intensity running distance during a match. It would be more effective to use the data of specialised tactical roles when prescribing training drills whilst replicating physical-tactical demands of play since applying generalist positions could lead to the misinterpretation of the contextualised data in selected positions.

No studies in the literature have attempted to compare match running performance analysed with the general positional analysis (e.g., CMP) to that with the specialised positional analysis (e.g., B2BM, CDM, and CAM) for determining their sensitivity. The comparison of the physical-tactical characteristics between the two different analyses has revealed that the player's physical-tactical demands of play can be under or overestimated if using the general positional analysis. When comparing FB and WB to their general role (WDP), 34% less and 15% more high-intensity distance was covered by respective tactical roles. Furthermore, the average numbers of high-intensity activities per match for 'Recover Run', as well as 'Support Play', 'Move to Receive/Exploit Space', and 'Run in Behind/Penetrate' could be overestimated for FB whilst these could be underestimated for WB except for 'Recovery Run' if using the general positional analysis. This trend could be due to WB running higher up the pitch to get involved in the attacking or the transition phase of play after the team regains the possession of the ball, and then producing 'Recovery Run' actions to get goal side when a turnover in possession occurs [20]. WB play akin to WM given that no differences were observed between them regarding all of the in-possession categories except for 'Over/Underlap' and 'Run in Behind/Penetrate'. On the other hand, CDM covered 30% less high-intensity distance compared to their general role (CMP) whilst CAM performed 22% more albeit with no statistical difference. Specifically, the average number of high-intensity 'Close Down/Press' actions performed by CDM ($n = 2$) and CAM ($n = 9$) per game could be over or underestimated with the use of the general positional analysis (CMP, $n = 5$) whereas CAM could perform less high-intensity 'Covering' actions per match. This clearly shows their different tactical duties during a match. For example, CAM are more likely to support the press whilst attackers are aggressively closing down the opponent on the ball or receiving the ball [39]; however, CDM tend to stay back to ensure defensive coverage whilst blocking space in front of the defence [24]. Moreover, in possession greater numbers of high-intensity 'Support Play', 'Move to Receive/Exploit Space', 'Run in Behind/Penetrate', and 'Break into Box' actions were executed for CAM compared to their general position (CMP); however, an opposite trend was seen for CDM. Thus, again coaches and practitioners should consider the specific tactical roles of players within the team when conditioning their players during training sessions. However, such detailed positional analysis is labour-intensive as it requires the observation of each player per match to be considered in light of numerous contextual factors that can influence match performance [4, 5]. Hence, the

development and adoption of machine learning approaches will be key in automatically classifying these specialised tactical roles [24].

Limitations

The samples of certain positions (e.g., CAM and WF) were relatively small compared to other positions, which could have affected the trends presented in this study. However, this could be due to the stringent game selection criteria for balancing and controlling data and/or such positions being more likely replaced with substitutions [40]. Moreover, as the match-to-match variability for high intensity distance (CV: 21–22%) and physical-tactical performance (CV: 62–67%) were high, the reader should always be aware that the present findings are hyper niche in relation to the EPL and the specific cultural and stylistic elements of that league, and thus may not necessarily apply to other elite leagues.

CONCLUSIONS

Using generalist positions is less sensitive to estimate player's actual isolated physical and contextualised demands and this may under and overestimate overall physical performance metrics of selected positions. The contextualised data trends presented could have huge practical implications for the design of positional play and position specific training sessions as well as recruitment. Finally, readers should be aware of the high degree of match-to-match variability exhibited in physical-tactical actions and understand that metric stability will be difficult to establish.

Conflict of interest

The authors have no conflict of interest to declare.

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Physiological responses of small-sided vs. regular games in youth volleyball players

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ABSTRACT: The aim of the present study was to evaluate the effects of two different formats of small-sided games (SSGs; 2 vs. 2 and 3 vs. 3) on physiological parameters in youth volleyball players. Twelve youth volleyball players (17.2 ± 7.44 years, 1.89 ± 0.6 m, 72.83 ± 8.57 kg) completed three different games formats (regular game (RG): 6 vs. 6, SSG3: 3 vs. 3 and SSG2: 2 vs. 2). associated with two pitch dimensions (i.e., 2 vs. 2 and 3 vs. 3 on 18×4.5 m; 6 vs. 6 on 18×9 m). Each player performed 4×5 min SSG with a recovery period of 1 min between bouts. All players were members of the same youth team and played in a professional league. They had at least 6 years of volleyball training and no current injuries. This study was carried out during the competitive period. Heart rate (HR), blood lactate ($[La^-]$), and rating of perceived exertion (RPE) were measured. Compared to RG, physiological (i.e., HR and $[La^-]$) and RPE responses were significantly higher during SSG3 and SSG2 (all $p < 0.05$; $\eta_p^2 = 0.77$, $\eta_p^2 = 0.65$, $\eta_p^2 = 0.30$, respectively). Moreover, HR and RPE were significantly higher in SSG2 compared to SSG3. In contrast, no significant differences were observed in $[La^-]$ between SSG2 and SSG3. These results suggest that the number of players influences the exercise intensity in small-sided volleyball games in youth players. Therefore, coaches could benefit from incorporating SSGs to manipulate the exercise intensity in youth volleyball players.

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INTRODUCTION

Small-sided games (SSGs) are very popular in team sports such as soccer, rugby [1] and Taekwondo [2], because they increase player's perception of specific tactical/technical issues, while promoting variations in physiological and physical stimuli [3, 4, 5]. Thus, SSGs allow for the identification a players' skill level, as well as proposing effectual training interventions in contextualized and situational manners [3].

SSGs offer multiple possibilities of factor variations. Indeed, several studies have analyzed the effect of modifying the number of players [6, 7], pitch size [8, 2], area per player [9], exercise duration [10, 11], coach encouragements [12], rule changes [1, 7, 8, 13], ball contacts [14], and different periods of play [15] on the physiological demands of soccer. Indeed, most studies [6, 7] have shown SSGs result in greater heart rate (HR), lactate concentration ($[La^-]$), and rating of perceived (RPE) exertion. Also, studies [8, 2] have found increases in physiological parameters (i.e., HR, $[La^-]$ and RPE), due to needing to cover an increased pitch area.

These studies confirm that, by altering these factors, it is possible to manipulate the overall physiological and perceptual workload placed on players. SSGs are increasingly being used to improve skill and physical fitness of team-sport athletes [16]. Given the importance of these physiological and skill qualities to team-sport performance, coaches are motivated to discover the most effective methods of developing these attributes in their athletes [17]. Although SSGs has been shown to provide a specific training stimulus that generally replicates the overall demands of team-sports, recent evidence suggests that it may not always reach levels needed to replicate the high intensity and the demands of competition [18].

Volleyball is an intermittent court sport, with multiple jumps and lateral movements performed throughout a match [19]. It requires well-developed speed, agility, upper- and lower-body muscular power, and maximal aerobic power ($\dot{V}O_{2max}$) [19]. Moreover, volleyball strategy implies a special consideration on game skills efficiency aspects where players must acquire all specific motions: serve, receive,

set, attack, block, and dig [20]. Smith *et al.* [21] suggested that physiological capacities play an important role in the preparation and selection of elite volleyball players. Furthermore, in volleyball, skill-based conditioning games offer a specific training stimulus to simulate the physiological demands of competition in youth volleyball players [22, 23]. Indeed, the improvement in physiological capacities in volleyball players was reportedly greater with the use of skill-based conditioning games vs. instructional training [22, 24, 25]. Gabbett, [22] suggested that conditioning coaches may use skill-based conditioning games during game-specific phases of training to elicit improvements in muscular power, speed, agility, and maximal aerobic power in order to promote the development of game-specific skills under fatigue. Thus, the use of skill-based conditioning games as training drills allows the simulation of movement patterns of team sports, while maintaining a competitive environment in which athletes must perform under pressure and fatigue [26, 27, 23].

To the best of our knowledge, no study has attempted to evaluate the physiological impact (i.e., HR, $[La^-]$ and RPE) of SSGs in youth volleyball players. Most SSG studies reported in the literature have been conducted in a limited number of team sports (i.e., soccer, rugby, handball, and basketball) [1, 28, 29].

Given that the task constraints manipulation could affect the physiological responses and, subsequently, the magnitude of performance improvement, SSGs may offer an additional challenge to volleyball players that would not normally be present in non-skill-related conditioning activities. The specificity principle dictates that the demands of a particular sport, or the demands of a task in which an athlete try to improve performance, will directly determine the manner in which the training should be performed. In addition, determining which format of SSGs would promote better physiological responses in volleyball is of practical significance. Therefore, the aim of the present study was to compare the effects of two formats of SSGs (SSG2: 2 vs. 2 and SSG3: 3 vs. 3) with a regular game (RG: 6 vs. 6) on exercise intensity in volleyball youth players. We hypothesized that the reduction of player number would elicit increases in the exercise intensity (higher physiological (HR and $[La^-]$) and perceptual (RPE) values). The goal of this study is to greater enable volleyball coaches and/or fitness coaches to determine training intensity when adopting SSG formats. Moreover, the findings could potentially provide valuable information to coaches when designing and promoting the use of SSGs training as part of a conditioning program.

MATERIALS AND METHODS

Subjects

Sample size was calculated using the software G*power (version 3.1.9.7; Kiel University, Kiel, Germany) with $\alpha = 0.05$ and power = 0.80 and based on the effect size (ES = 0.4) reported by Praça *et al.* [30]. A minimum of 10 participants for each group was required for inclusion in the present study. Due to potential dropout, 12 participants were recruited.

Twelve young volleyball players (age: 17.2 ± 7.44 years; height: 18.9 ± 0.05 m; body mass: 72.83 ± 8.57 kg) voluntarily participated in this study. All players were members of the same youth team and played in a professional league. They had an experience of at least 6 years of volleyball training. Subjects were chosen by the responsible technical committee, so that the team were balanced regarding the positions of the players (setter, outside hitter, opposite hitter, middle blocker, libero and defensive specialist). This precaution was taken to allow the team to maintain a high level of competitiveness and concentration during the games. Substitute players and those with injuries were excluded from the study. All the players and their parents/legal guardians were notified about the research design and its requirements, as well as the potential benefits and risks. Each participant gave written informed consent prior to the start. The study was approved by the local ethics committee, and was conducted in a manner consistent with the institutional ethical requirements for human experimentation in accordance with the Declaration of Helsinki 1964 and its further amendments.

Experimental procedure

To investigate the effect of two volleyball SSGs formats (i.e., SSG2: 2 vs. 2 and SSG3: 3 vs. 3) with RG (i.e., 6 vs. 6) on physiological responses: two pitch dimensions and three formats were employed [i.e., 2 vs. 2 and 3 vs. 3 on 18×4.5 m (81 m^2); 6 vs. 6 on 18×9 m (162 m^2)]. The pitch ratio per player (pitch area divided by the number of players: $\text{m}^2 \times \text{player}$) [31] was $1:20.2 \text{ m}^2$, $1:13.5 \text{ m}^2$ and $1:13.5 \text{ m}^2$, respectively for 2 vs. 2, 3 vs. 3 and 6 vs. 6. Each player performed 4×5 min SSG with a recovery period of 1 min between bouts. The training intervention was conducted during the competition period from 2019–2020. Participants usually trained using the SSGs with varying numbers of players; but they have been further familiarized with the specific SSG formats (i.e., 2 vs. 2; 3 vs. 3 and 6 vs. 6) during three weeks before the experiment. A physician staff recommended and monitored the dietary regime and hydration status of each player before and after every training session.

The SSGs consisted of teams of 2 or 3 outfield players being played on 18×4.5 m pitch, whereas the RG consisted of 6 players a-side played on 18×9 m pitch. Players were divided regarding their positions (setter, outside hitter, opposite hitter, middle blocker, libero and defensive specialist). Both SSGs had the same duration and lasted for 4×5 min with 1 min of passive recovery between games, while the RG consisted of a set of 25 points with two technical time-out of 1 min and 2 voluntary time-out. Moreover, both SSGs and RG involved normal match rules with no other added conditions. No specific tactical instructions were imposed to players within the games. The SSGs were performed under the supervision of their coach and the responsible technical committee to keep up a high work rate. For this reason, a large number of balls were placed near to the net to ensure a continued play (figure 1). Each game was preceded by a 20-min standardized warm-up consisting of low-intensity running,

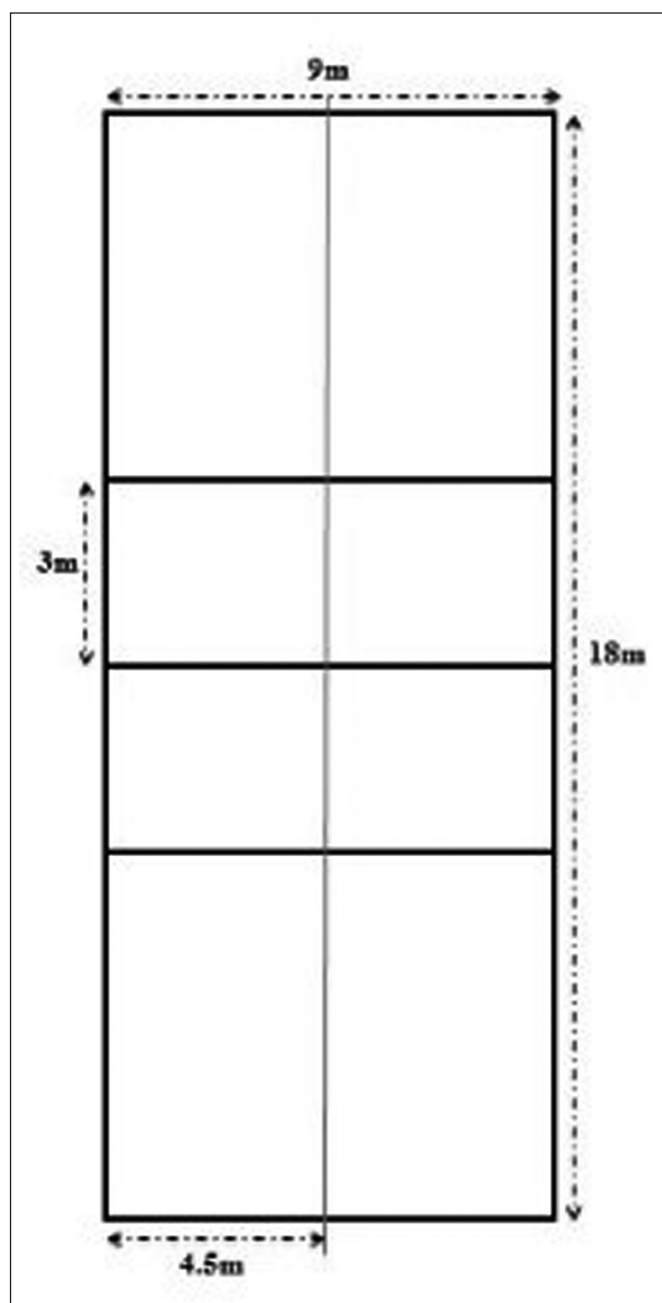


FIG. 1. Volleyball court for SSGs.

striding, and dynamic stretching with a final 5 min of ball passing. All games were played at the beginning of the training sessions. The order of RG on Monday in the third week, SSG3 on Monday in the fourth week, and SSG2 on Monday in the fifth week of the investigation. As requested by the coach, SSGs were not scheduled the day before a competitive game.

Heart rate (HR) was continuously monitored throughout the SSGs and the RG by HR monitors (Polar Team Sport System, Polar-Electro OY, Kempele, Finland) and recorded at 5-s intervals. Individual mean HR during RG and SSGs were determined to indicate the overall

intensity. HR data were therefore expressed as percentage of HR_{max} ($\%HR_{max}$). Capillary blood samples were taken from an earlobe at one minute from the end of the last bout of SSG and RG [32]; and immediately analyzed for lactate using a portable amperometric microvolume lactate analyzer (Lactate Pro, Arkay, Japan). RPE scores (10-point scale [33]) were recorded immediately after the end of exercises (SSG2, SSG3 and RG) to determine how hard the players perceived the session (internal intensity and exercise load of the session) [34, 35]. These scores had been recorded during the two weeks prior to the investigation to ensure subjects familiarization with such tools. SSGs and RG were performed at the same time-of-day (from 16:00 to 18:00) to limit the effects of the circadian variations on the measured variables, particularly on HR measures [36].

Statistical analysis

Data are presented as means and standard deviations (means $\pm$ SD). Before using parametric statistical test procedures, the normal distribution of data was verified. A two-way analysis of variance (ANOVA) ([periods] $\times$ [games]) with repeated measures was used to test for differences in performance measures (dependent variable) between the different periods within each SSGs (SSG2, SSG3) or the RG, independent variable. When the ANOVA indicated significant factor or interaction effects, a Bonferroni-corrected post hoc test was applied to investigate specific differences. The Shapiro-Wilk's test was used to verify normal distribution. Effect sizes (Cohen's d) for pairwise comparisons were calculated with the pooled standard deviations and considered as small (> 0.2 – 0.6), moderate (> 0.6 – 1.2), large (> 1.2 – 2.0), very large (> 2.0 – 4.0) and extremely large (> 4.0) [37]. All statistical analyses were performed using the software package STATISTICA (StatSoft®, Maisons-Alfort, France) and statistical significance was set, *a priori*, at $P < 0.05$.

RESULTS

HR responses

The one-way ANOVA showed a significant effect of game format ($F_{(2,22)} = 37.64$; $P < 0.001$; $\eta_p^2 = 0.77$) on the $\%HR_{max}$. Post-hoc analysis showed that the $\%HR_{max}$ was significantly higher during SSG2 compared to the SSG3 ($83.45 \pm 4.06\%$ vs. $77.12 \pm 2.51\%$; $P < 0.001$; $d = 1.41$) and to the RG ($83.45 \pm 4.06\%$ vs. $71.67 \pm 4.55\%$; $d = 2.41$). Moreover, $\%HR_{max}$ was significantly higher during SSG3 compared to RG ($77.12 \pm 2.51\%$ vs. $71.67 \pm 4.55\%$; $P < 0.001$; $d = 1.16$) (Figure 2). The coefficient of variation for the $\%HR_{max}$ during different games formats is presented in table 1.

RPE scores

The one-way ANOVA showed a significant effect of game format ($F_{(2,22)} = 20.75$; $P < 0.001$; $\eta_p^2 = 0.65$) on the RPE. Post-hoc analysis results revealed that RPE scores were significantly higher during SSG2 compared to the SSG3 (7.25 ± 0.59 vs. 6 ± 1.08 ; $P = 0.005$; $d = 0.92$) and to the RG (7.25 ± 0.59 vs. 5 ± 0.81 ;

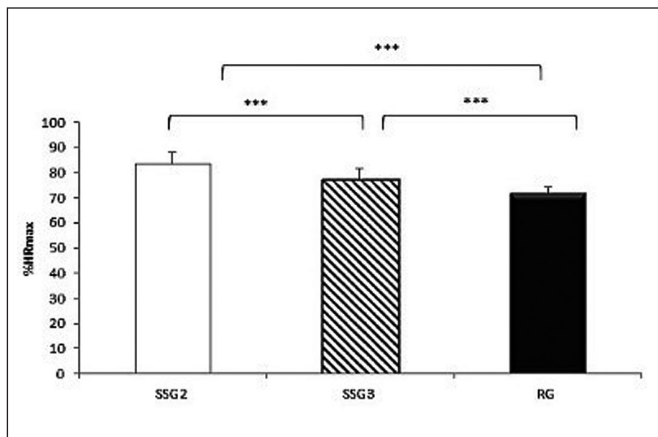


FIG. 2. Percentage of maximum heart rate (%HR_{max}) during SSG2, SSG3 and RG. *** significant difference at $P < 0.001$.

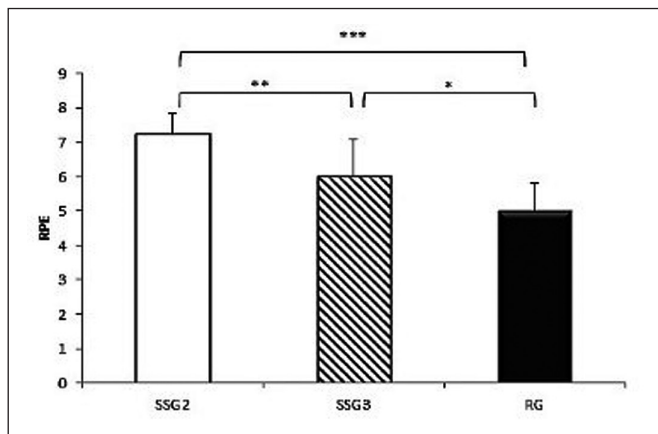


FIG. 3. RPE values during SSG2, SSG3 and RG *** significant difference at $P < 0.001$, ** significant difference at $P < 0.01$ and * significant difference at $P < 0.05$.

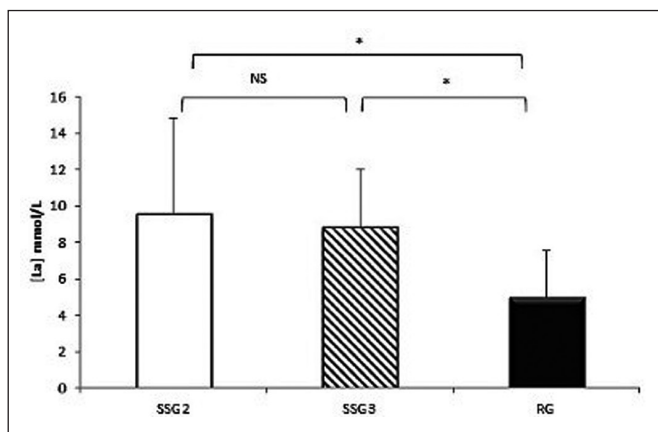


FIG. 4. Lactate concentrations [La⁻] during SSG2, SSG3 and RG * significant difference at $P < 0.05$; NS: no significant difference.

TABLE 1. Coefficient of variation for the physiological parameters during SSG formats

Parameters	SSG formats		
	2 vs. 2	3 vs. 3	6 vs. 6
%HR _{max}	5.1%	3.4%	6.6%
RPE	8.6%	18.8%	17.1%
[La ⁻]	58.0%	57.7%	53.8%

$P < 0.001$; $d = 1.98$). Moreover, RPE was significantly higher during SSG3 compared to RG (6 ± 1.08 vs. 5 ± 0.81 ; $P = 0.027$; $d = 0.89$) (Figure 3). The coefficient of variation for RPE scores during different games formats is presented in table 1.

Blood lactate concentration

The one-way ANOVA showed a significant effect of game format ($F_{(2,22)} = 4.80$; $P = 0.019$; $\eta_p^2 = 0.30$) on [La⁻]. Post-hoc analysis results of the [La⁻] reported that there was no significant difference between SSG2 and SSG3 (9.54 ± 5.3 vs. 8.82 ± 3.18 mmol/L; $P = 0.65$). However, the [La⁻] was significantly higher in SSG2 (9.54 ± 5.3 vs. 4.99 ± 2.57 mmol/L; $P = 0.026$; $d = 0.75$) and SSG3 (8.82 ± 3.18 vs. 4.99 ± 2.57 mmol/L; $P = 0.045$; $d = 1.07$) compared to RG (Figure 4). The coefficient of variation for blood lactate concentration during different games formats is presented in table 1.

DISCUSSION

The purpose of this study was to investigate the physiological (HR and [La⁻]) and perceptual (RPE) responses of SSGs and RG in youth volleyball players. Compared to RG, all physiological and perceptual responses (i.e., HR, [La⁻] and RPE) were significantly higher during SSG3 and SSG2. Moreover, HR and RPE were significantly higher in SSG2 compared to SSG3. In contrast, no significant differences were observed in [La⁻] between SSG2 and SSG3. Given the lack of studies on the subject of intensity in SSG in volleyball [38], the results of the present study will be compared with (i) those of team sports and (ii) the specificities and requirements of volleyball.

The results of this study demonstrate that SSGs provide greater physiological responses than RG. Indeed, %HR_{max} recorded during SSG2 and SSG3 was significantly higher than those of RG (83.45% vs. 77.12% vs. 71.67%, respectively). Further, these results are supported by those of Dellal *et al.* [15] and Jones and Drust [3] in soccer players, who showed that players presented higher %HR_{max} during SSGs vs. RG. The higher %HR_{max} recorded during SSGs could be explained by the greater technical, physical and tactical implication of all players both in offensive and defensive phases induced by SSGs. These results are likely due to the increase of shifting distance,

the reduction of recovery period, and a higher incentive for players in SSGs vs. RG.

It is noteworthy that HR responses to exercise are generally not considered as the best indicator to examine the physiological requirements during SSGs. Indeed, the RPE has been used as an alternative measure of the soccer-training load [39], which could allow the analysis of the global internal load [3, 34]. The results of the present study showed that RPE values were higher in SSG2 and SSG3 than RG (7.25 and 6 vs. 5 A.U, respectively). Our results are in contrast with those of Dellal et al. [15] who found that RPE values were lower during SSGs. Indeed, RG appeared to be perceived easier than all SSGs situations. It would be expected from this data that the volleyball rule could induce a lower intensity within RG both concerning the physiological activities, which explain that players prefer this type of training.

Interestingly, in spite of the high-intensity of play observed during SSGs of the present study, $[La^-]$ was higher during the SSGs than during RG (9.54 vs. 8.82 vs. 4.99 mmol/l, respectively to SSG2, SSG3 and RG). Indeed, low values of $[La^-]$ during the RG in our experiment is the effect of natural game characteristics (serving and changing position). It results in recovery and rather low level of $[La^-]$ values. In general, in a volleyball game low $[La^-]$ (2.54 ± 1.21 mmol/l) during and after matches and increases of free fatty acids indicates that energy during the short exercise periods is mainly supplied by a breakdown of creatine phosphate, while aerobic pathways restore the energy sources during rest periods [40]. Due to the higher intensity performed during the SSGs, the anaerobic energy turnover would be expected to contribute more to the muscle metabolism in SSGs as compared to RG. In contrast to our findings, Dellal et al. [15] found, in soccer players, a higher $[La^-]$ within RG than SSGs. Dellal et al. [15] explained the lower $[La^-]$ recorded in soccer SSGs by the short duration of resulting in a higher reliance on ATP and CP breakdown rather than anaerobic glycolysis.

SSGs are often used as part of regular training programs in various forms, depending on the aim and the philosophy of the coach [41]. Moreover, it allows more time spent managing the ball under game-like conditions compared with generic training [25, 42]. Thus, most exercise sessions in team sports have SSG played with a reduced number of players on a smaller area than the regular official game pitch size [39]. Given that it has been shown that the physiological responses during SSGs are higher than within RG, it is feasible to suggest that SSGs may be used as a physical training modality for volleyball [24]. Indeed, all measured physiological responses in the present study provide informative detail, but it is important to study these physiological results within different SSG formats and pitch dimensions.

This study extends the findings of others demonstrating that a higher number of players can significantly alter the physiological responses during SSGs [39, 43, 44]. In the present study, SSG2 had the highest %HR_{max} (83.45%) compared with SSG3 (77.12%). In this context, Dellal et al. [45] and Rampinini et al. [39] investigated the

effect of changing number of players in football on HR responses in different conditions. The authors observed a higher %HR_{max} and greater HR reserve with a reduced number of players. These findings are comparable to the results of Casamichana et al. [10] who revealed that a larger area per player determines a higher effective playing time, %HR_{max}, time spent above 90% HR_{max}, and RPE. The highest %HR_{max} reported in our study could be explained such that the recovery for the inactive player during SSG3 meant more tactical combinations could be performed. Accordingly, this may increase active recovery, and thus prepare the players for high intensities and to restart in the subsequent offensive or defensive process. Indeed, these results can be explained by the greater number of opponents in SSG3 that increases the uncertainty of the player regarding their actions.

In general, studies have shown that SSG formats with fewer players elicit greater RPE than the larger formats in soccer [34, 39, 46, 47, 48]. The latter findings are concordant with our results, where SSG2 induced significantly higher RPE responses compared to SSG3 (7.25 vs. 6 A.U respectively). These authors explained that the increase of pitch ratio per player induced higher RPE values, probably due to the increase of running distance, the greater activity, the reduction of recovery period within the SSG, and that players were systematically more stimulated. The decrease of RPE within SSG3 in our results can be explained by the collaboration between players allowing an inactive recovery. In addition, increasing the numbers of player can promote the teamwork and stimulate the partnership.

Unlike previous studies [1, 15, 49], we showed no significant differences in $[La^-]$ between SSG2 and SSG3 (9.54 vs. 8.82 mmol/l, respectively). This could be explained by the characteristics of the volleyball game; in both SSG2 and SSG3 format, players are quite free to move and change their position. Furthermore, since the specificity of volleyball requires much more placement than movement, the two forms of SSGs require the same time motion where the players must imperatively participate in each action, where, 0, 1 or 2 players are on block and 1, 2 or 3 in the back defense [25]. The specificity of this sport obliges the defender to cover a wider space (forward and backward movement) for the 1 vs. 1 game as it also forces the blocker to block 2 spikers across the net (lateral or cross movement). These findings are useful for coaching and developing the technical skills of novice players because it can promote a higher individual participation and stimulate the technical and physiological aspects.

Concerning the small number of players participating in this study ($n = 12$), most studies in SSG have used a small number of subjects in their research, and many of them have used the same number as of our sample size [22]. Moreover, in the present study, 12 players fulfilled the inclusion criteria for participating in the research; which permitted all players to participate in the RG. Although the present study provides a novel addition to the literature concerning physiological responses in volleyball using two forms (SSG and RG) in youth players and the intensity of SSG in volleyball, there are some

limitations that should be considered. First, the results cannot be generalized to all volleyball training and can only be applied to youth players. Future studies should compare the effects of RG with those of SSGs for physical and tactical learning of adult players and the collective organization of teammates. Furthermore, the lack of the use of video and GPS in this study precludes more accurate data on the players' motion. Accordingly, further studies with RG and SSG should consider using GPS and video analysis to ascertain more detailed insight into specific movement patterns. In terms of practical implications, coaches should consider using instruments that allow them to monitor intensity among players during training. In addition, coaches can consider these two forms of SSG (2 vs. 2 and 3 vs. 3) as a part of training when planning. Finally, given that the coach was involved during the sessions, there are issues of potential bias given the personal relationships of the coach to the players, this causing artificial changes in motivation, extraneous to the study parameters. However, given that coaches are almost always involved in player training, it was deemed acceptable for the purposes of this study.

CONCLUSIONS

The main findings of the present study suggest that small-sided games elicit higher physiological responses than regular game. In this context, it appears that the higher physiological responses of youth volleyball players during SSGs are linked with the greater

involvement of each player in the game. Within small-sided games, changing the number of players elicited significant changes in heart rate and rating of perceived exertion, while there was no significant difference in blood lactate. Moreover, the high intensity of small-sided games 2 compared with small-sided games 3 is likely attributable to the pitch area per player. Finally, the results of this study could help coaches/practitioners in planning seasonal programs and multifunctional aspects of specific training sessions in youth volleyball players and to improve their physiological and/or technical training.

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The authors declare that they have no conflict of interests relevant to the content of this manuscript.

The results of this study do not constitute endorsement of the product by the authors or the National Strength and Conditioning Association.

Competing Interests

None of the authors declare competing financial interests.

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Positional and temporal differences in peak match running demands of elite football

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ABSTRACT: Temporal changes in the total running demands of professional football competition have been well documented, with absolute running demands decreasing in the second half. However, it is unclear whether the peak match running demands demonstrate a similar decline. A total of 508 GPS files were collected from 44 players, across 68 matches of the Australian A-League. GPS files were split into the 1st and 2nd half, with the peak running demands of each half quantified across 10 moving average durations (1–10 min) for three measures of running performance (total distance, high-speed distance [$> 19.8 \text{ km} \cdot \text{h}^{-1}$] and average acceleration). Players were categorised based on positional groups: attacking midfielder (AM), central defender (CD), defensive midfielder (DM), striker (STR), wide defender (WD) and winger (WNG). Linear mixed models and effect sizes were used to identify differences between positional groups and halves. Peak running demands were lower in the second half for STR across all three reported metrics (ES = 0.60–0.84), with peak average acceleration lower in the second half for DM, WD and WNG (ES = 0.60–0.70). Irrespective of match half, AM covered greater peak total distances than CD, STR, WD and WIN (ES = 0.60–2.08). Peak high-speed distances were greater across both halves for WIN than CD, DM and STR (ES = 0.78–1.61). Finally, STR had lower peak average acceleration than all positional groups across both halves (ES = 0.60–1.12). These results may help evaluate implemented strategies that attempt to mitigate reductions in second half running performance and inform position specific training practices.

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INTRODUCTION

Traditionally the physical demands of professional football match play have been quantified as absolute match running volumes using either video match analysis systems or global positioning systems (GPS) [1, 2]. As such, the physical demands of football and the intra- and inter-match differences in physical match demands (total distance (TD), high-speed distance [$> 19.8 \text{ km} \cdot \text{h}^{-1}$] (HSD) and acceleration profiles) have become routinely reported [2–4]. Separately, research has explored the effects of acute reductions in physical performance during match-play, as represented by temporal changes in physical demands throughout a match [3]. Recent methods have quantified changes in physical outputs across discrete periods of match-play, such as between halves or distinct 15 min periods within halves e.g., 0–15 min, 15–30 min [5–7]. Collectively, this research has demonstrated that physical output is reduced during the second half, with the greatest reduction occurring in the final 15 minutes of the match [8]. Interestingly, this reduction during the final stages of a match coincides with a reported increase in goal scoring opportunities [9–12]. Consequently, the ability to perform at

higher intensities for shorter periods when fatigued appears crucial to creating or denying goal scoring opportunities [11, 12]. As such, understanding the match demands and how these fluctuate throughout a match can help inform training practices to prepare players for competition.

Quantifying the physical demands of match-play provide context for training prescription and preparing players for competition. Recent methods have explored the most physically demanding periods of match-play through quantifying the peak match running demands for a range of short epochs rather than absolute running volumes for arbitrary epochs [13–15]. These peak match running demands are calculated using a moving average duration, where the highest observed physical output for selected metrics are calculated at incremental discrete time periods (e.g. 1–10 min), irrespective of match time [13]. Through calculating the peak match intensities, the most physically demanding periods of a match can be identified and replicated through training and conditioning drills. For example, the peak distance covered over 5 min during a match could be used to inform a training

drill of 5 min in duration. Importantly, the use of a rolling average (e.g. 0–1, 0.1–1.1, 1.2–2.2 min) has been shown to be more accurate than assessing peak match running demands using predefined 1 min periods (e.g. 0–1, 1–2, 2–3 min), with the predefined periods underestimating peak match running demands by ~7–25% [14]. Such variance between analysis techniques reflects that the peak match running demands often traverse multiple predefined periods, meaning that performance staff may interpret match demands and prescribe training below match intensities [16, 17].

With football being stochastic in nature and players frequently required to perform at near maximal intensities, the mechanisms underlying acute changes to physical performance are multi-factorial and require a holistic approach to quantify [18, 19]. As such, monitoring physical performance data may not only be used to inform training practices, but also to help assess both individual and team physical performance and acute change to physical demands during match play [8]. One such important consideration is a players position, with position related differences observed for both total match outputs [20] and peak match running demands [13]. Additionally, the available research strongly demonstrates that physical output declines between halves in football, with the magnitude of reductions being impacted by multiple factors including fatigue, the use of pacing strategies or differing match situations (Bradley & Noakes, 2013; Di Salvo *et al.*, 2009; Mohr *et al.*, 2003). However, there is limited research on changes in peak match running demands between halves, with only two papers reporting such differences [21, 22]. When all positional groups were pooled, reductions in peak total distance across the analysed time periods of 1, 3, 5 and 10 min were observed, with HSD ($> 19.8 \text{ km} \cdot \text{h}^{-1}$) and sprint distance ($> 25 \text{ km} \cdot \text{h}^{-1}$) being maintained between halves [22]. Similarly, when accounting for positional groups, Casamichana, Castellano [21] reported moderate reductions in peak total distance covered during the second half for central defenders (CD) across 3, 5 and 10 min window durations, with wide defenders (WD) and wingers (WIN) also having moderate reductions for the 10 min duration. Further, minimal differences were observed between halves for high metabolic load distance, with average metabolic power found to be reduced for all positional groups in the second half [21].

While position-related differences have been observed for both total match physical outputs [20] and peak match running demands [13], further assessment of between half differences by positional group is warranted. Of the single study that reported on the between half positional differences in peak match running demands [21], they included limited windows (1, 3, 5 and 10 min) and reported on total distance, high metabolic load distance and average metabolic power. As such, despite pooled positional data available in the literature [22], the between-half positional differences for peak match running demands of HSD and average acceleration (AveAcc) are yet to be reported on. As such, this study aimed to report on the within- and between-halves and positional groups differences in peak match running demands across a range

of durations (1–10 min) for commonly assessed metrics to help progress match performance analysis and better inform training prescription.

MATERIALS AND METHODS

An observational design was used to compare the positional differences in peak match intensities across incremental moving average between 1–10 minutes, between halves in elite football players. Data were collected from 44 professional footballers playing in the same team competing within the Australian Hyundai A-League. Data were collected across three seasons of competitive A-League matches, consisting of 68 matches, for a total of 508 individual match observations (13 ± 10 matches per player, range 1–43). With majority of peak match running demands occurring prior to the 70th minute [23], data were only included if players participated in more than 70 minutes of a match. These observations were representative of the entire playing group, with match files categorised according to position, as Attacking Midfielder (AM; $n = 6$, files = 68), Central Defender (CD; $n = 10$, files = 118), Defensive Midfielder (DM; $n = 6$, files = 91), Striker (STR; $n = 4$, files = 46), Wide Defender (WD; $n = 9$, files = 105) and Winger (WNG; $n = 9$, files = 80); where the team in question typically used a 4-2-1-3 formation. Prior to collection of data, ethical approval was attained from La Trobe University (HREC#: 18056).

Activity Profile

Player activity profiles were recorded during the entirety of match-play using 18 Hz (10 Hz GNSS) portable GPS units (STATSports, Northern Ireland) that were placed between the scapulae in a custom-made harness under the playing jersey. All GPS devices were turned on 30 min prior to match commencement to allow for satellite acquisition. The GPS units employed are valid and reliable in measuring locomotor speeds of team sport athletes [24, 25]. Following each match, GPS files were downloaded using proprietary software (STATSports, Northern Ireland) with the raw GPS files (inclusive of added time) were exported into statistical software (R Studio, v1.2.5033) for further analysis. The raw exported speed trace was filtered using a 4th order one-way Butterworth filter with a cut-off frequency of 1 Hz. Individual data points, in which running speeds exceeded $10 \text{ m} \cdot \text{s}^{-1}$ and acceleration/deceleration values that exceeded $6 \text{ m} \cdot \text{s}^{-2}$ were classified as technical errors and replaced with zero values.

From the GPS data, three commonly assessed measures of running intensity were chosen for assessment: total distance covered, high-speed distance covered ($> 19.8 \text{ km} \cdot \text{h}^{-1}$) and average acceleration, with total and high-speed distance made relative to playing time ($\text{m} \cdot \text{min}^{-1}$). Average acceleration was calculated through the summation of all absolute acceleration and deceleration speeds which were then averaged over a defined time duration to provide an indication of the total acceleration requirements of match-play [26]. Although the consolidation of both accelerations and decelerations into one variable may conceal the underlying mechanisms responsible for the load, it has been suggested that assessing both variables

together will better reflect the intensity of the activity [16]. To quantify peak match intensities, a moving average technique was applied to all three of the match output variables for ten incremental time epochs (i.e. 1–10 min), with the maximum value from each epoch recorded and then fitted using a power law curve [13, 27].

Statistical Analysis

Statistical analyses were conducted using R Studio statistical programming software (v1.2.5033, R Core Development Team, Vienna) using the *nlme* [28] and *lme4* [29] packages to conduct linear and non-linear mixed effects analysis. Non-linear mixed models were used to calculate exponent and slope values for the power law model, with differences in peak match running demands of TD, HSD and AveAcc profiles between positions and halves assessed using linear mixed models. In the linear mixed model, fixed effects were included for intensity period, position [six levels: AM, CD, DM, STR, WD and WIN] and match halves (two levels: first half and second half). A random intercept was included for player and an exponential correlation structure, with a nugget effect, to account for temporal correlation between intensity periods. Linear mixed models were also used to assess between position and half measures of absolute TD, HSD and AveAcc, with a fixed effect included for match half (two levels: first half and

second half). Raw unit differences between positional groups and halves, at each intensity period or half, were converted to standardised mean differences (SMD) by dividing the mean, raw unit difference by the within-subject standard deviation (SD) attained from the random effects (i.e., the square root of the residual variance term). The magnitude of the SMD was quantified using the following qualitative descriptors: trivial (<0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0), very large (2.0–4.0) and extremely large (>4.0) [30]. A worthwhile difference was determined as a moderate effect size (> 0.6), with the imprecision of model regression parameter estimates are expressed using 95% confidence intervals (CIs).

RESULTS

Absolute measures of total match physical output are presented in Table 1, with AM displaying higher absolute and relative TD than CD, WD and STR during the match (ES = 1.63–2.04). Further, WIN performed greater absolute HSD than all other positional groups, except AM (ES = 1.56–2.7). No positional differences were observed for AveAcc. The non-linear relationships of the peak match intensity power law models presented in Table 2, with differences between positional groups and halves presented in Figure 1. Attacking mid-fielders covered more relative TD than all other positional groups

TABLE 1. Absolute and relative match outputs. Data presented as mean $\pm$ SD. Data in brackets indicate relative distances covered ($\text{m} \cdot \text{min}^{-1}$).

	Variable	Attacking Midfielder	Central Defender	Defensive Midfielder	Striker	Wide Defender	Winger
Match Duration (min)	1 st Half	47 $\pm$ 1	47 $\pm$ 1	47 $\pm$ 1	47 $\pm$ 1	47 $\pm$ 1	47 $\pm$ 1
	2 nd Half	50 $\pm$ 1	50 $\pm$ 2	50 $\pm$ 2	49 $\pm$ 2	50 $\pm$ 2	50 $\pm$ 2
	Match	97 $\pm$ 2	97 $\pm$ 2	97 $\pm$ 2	96 $\pm$ 2	97 $\pm$ 2	97 $\pm$ 2
Total Distance (m)	1 st Half	5645 $\pm$ 362 ^{be} (119 $\pm$ 10) ^{be}	5070 $\pm$ 469 (107 $\pm$ 10) ¹	5261 $\pm$ 623 (111 $\pm$ 13) ¹	4742 $\pm$ 376 (101 $\pm$ 8) ¹	5036 $\pm$ 410 (106 $\pm$ 9)	5396 $\pm$ 549 (114 $\pm$ 11) ¹
	2 nd Half	5624 $\pm$ 543 ^{bde} (114 $\pm$ 12) ^{bde}	5078 $\pm$ 457 (102 $\pm$ 10)	5308 $\pm$ 376 (106 $\pm$ 8)	4627 $\pm$ 412 (94 $\pm$ 8)	5087 $\pm$ 471 (103 $\pm$ 10)	5362 $\pm$ 720 (107 $\pm$ 14)
	Match	11269 $\pm$ 689 ^{bde} (116 $\pm$ 8) ^{be}	10149 $\pm$ 835 (104 $\pm$ 9)	10569 $\pm$ 863 (109 $\pm$ 9)	9369 $\pm$ 723 (97 $\pm$ 7)	10123 $\pm$ 764 (105 $\pm$ 8)	10758 $\pm$ 1142 (110 $\pm$ 11)
High-Speed Distance (m)	1 st Half	354 $\pm$ 102 ^b (7 $\pm$ 2)	248 $\pm$ 101 (5 $\pm$ 2)	255 $\pm$ 106 (5 $\pm$ 2)	270 $\pm$ 68 (6 $\pm$ 1)	337 $\pm$ 124 (7 $\pm$ 3)	450 $\pm$ 135 ^{bcd} (9 $\pm$ 3)
	2 nd Half	347 $\pm$ 113 (7 $\pm$ 2)	267 $\pm$ 118 (5 $\pm$ 2)	253 $\pm$ 91 (5 $\pm$ 2)	254 $\pm$ 87 (5 $\pm$ 2)	349 $\pm$ 127 (7 $\pm$ 3)	449 $\pm$ 148 ^{bcd} (9 $\pm$ 3)
	Match	701 $\pm$ 171 ^b (7 $\pm$ 2)	515 $\pm$ 195 (5 $\pm$ 2)	508 $\pm$ 169 (5 $\pm$ 2)	524 $\pm$ 110 (5 $\pm$ 1)	687 $\pm$ 222 (7 $\pm$ 2)	899 $\pm$ 259 ^{bcd} (9 $\pm$ 3)
Average Acceleration ($\text{m} \cdot \text{s}^{-2}$)	1 st Half	0.63 $\pm$ 0.06	0.61 $\pm$ 0.05	0.65 $\pm$ 0.05	0.57 $\pm$ 0.02	0.62 $\pm$ 0.05	0.64 $\pm$ 0.06
	2 nd Half	0.59 $\pm$ 0.07	0.57 $\pm$ 0.07	0.61 $\pm$ 0.04	0.53 $\pm$ 0.04	0.59 $\pm$ 0.06	0.60 $\pm$ 0.07
	Match	0.61 $\pm$ 0.06	0.59 $\pm$ 0.05	0.63 $\pm$ 0.04	0.55 $\pm$ 0.03	0.60 $\pm$ 0.05	0.62 $\pm$ 0.06

Differences indicated if standardised mean difference is greater than 0.6. a = greater than AM, b = greater than CD, c = greater than DM, d = greater than STR, e = greater than WD, f = greater than WIN. 1 = greater than second half.

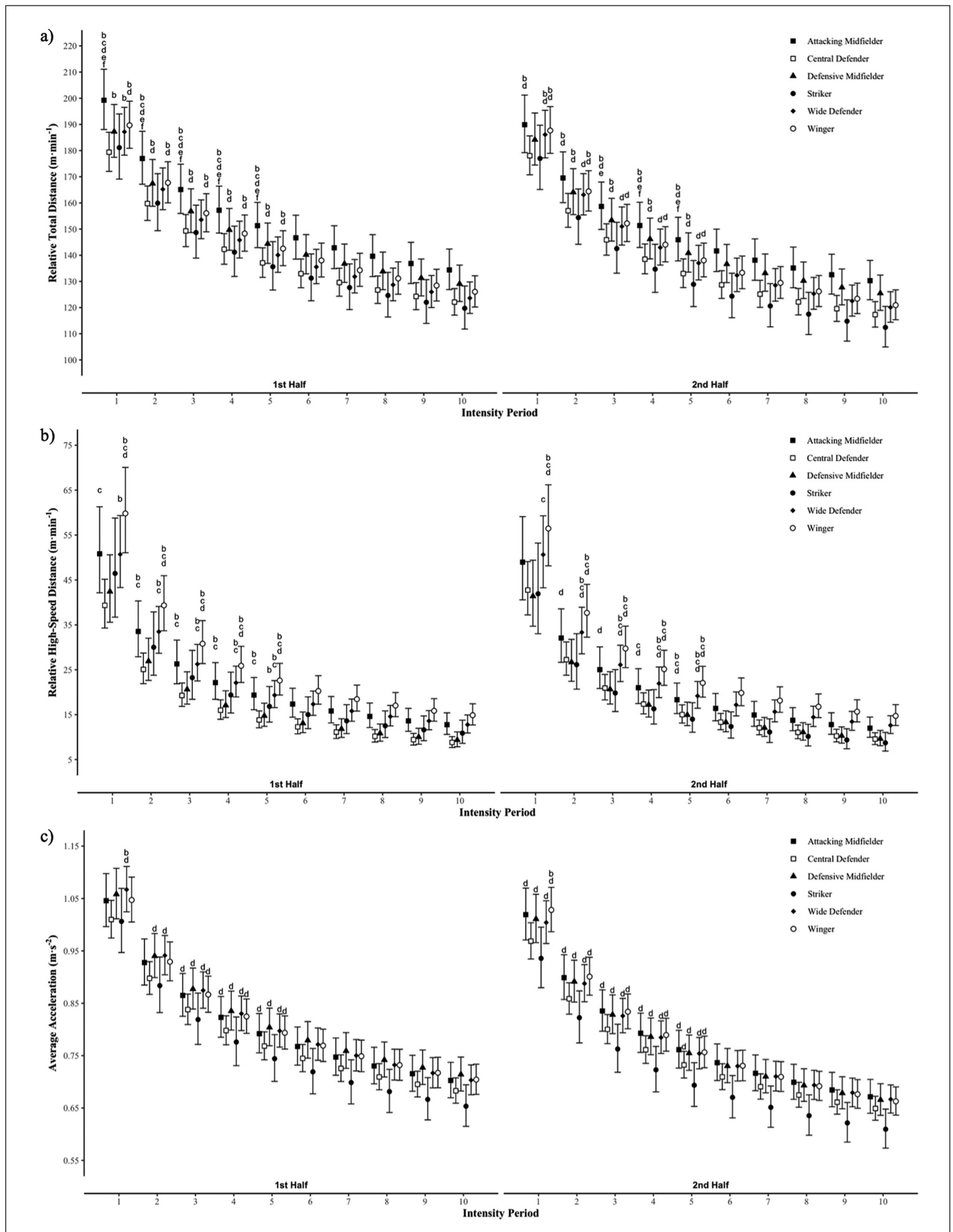


FIG. 1. A positional comparison of peak match running demands of a) relative total distance, b) relative high-speed distance and c) average acceleration across each match half. Differences indicated if standardised mean difference is greater than 0.6. a = greater than Attacking Midfielder, b = greater than Central Defender, c = greater than Defensive Midfielder, d = greater than Striker, e = greater than Wide Defender, f = greater than Winger.

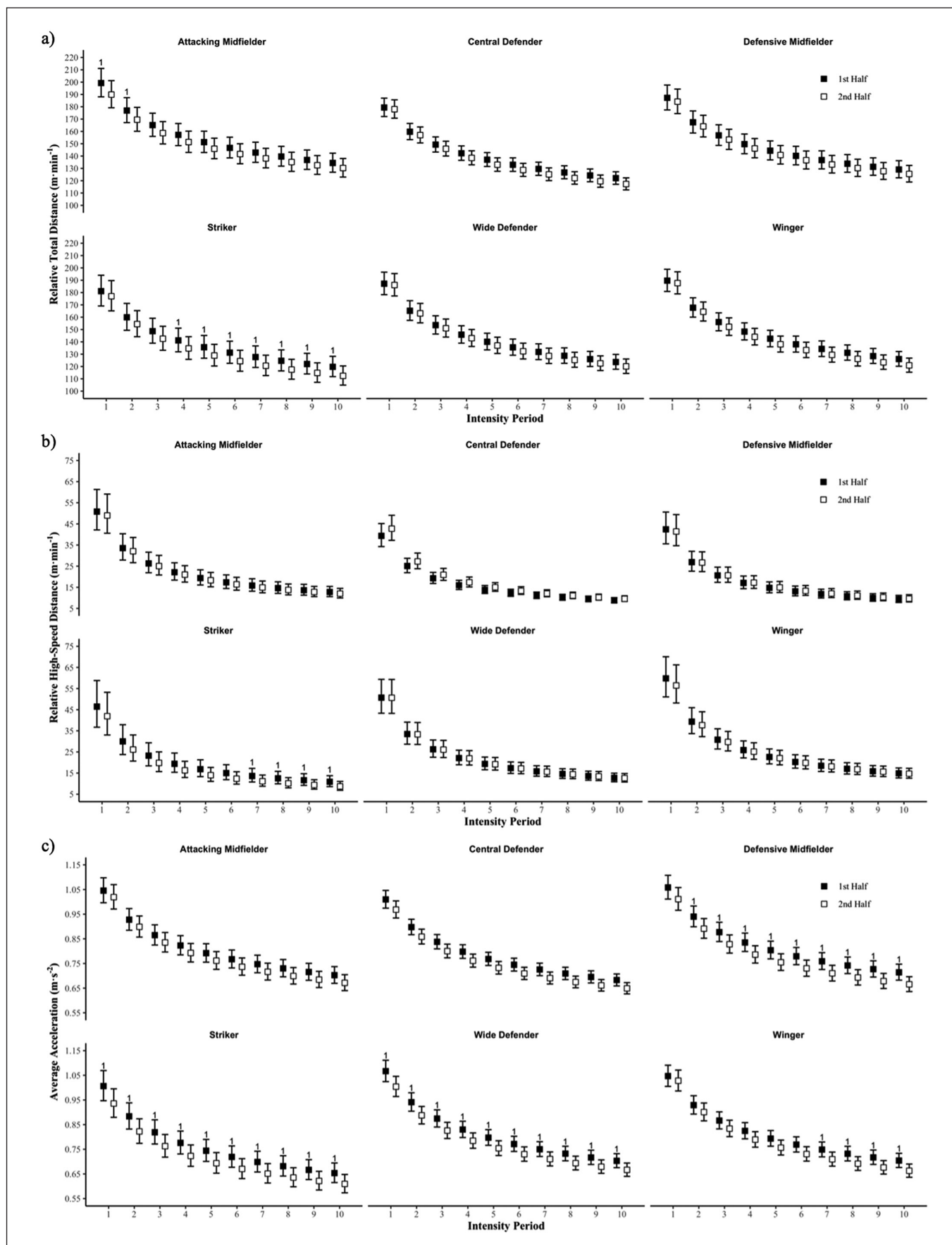


FIG. 2. A between half comparison of peak match running demands of a) relative total distance, b) relative high-speed distance and c) average acceleration for each positional group. Differences indicated if standardised mean difference is greater than 0.6. 1 = greater than 2nd half.

TABLE 2. Non-linear relationships of power law models. Data presented as mean $\pm$ 90% CI.

Variable		Attacking Midfielder	Central Defender	Defensive Midfielder	Striker	Wide Defender	Winger	
Relative Distance (m · min ⁻¹)	Intercept	1 st	199	180	187	182	188	189
		Half	(188–211)	(159–205)	(163–214)	(157–211)	(165–215)	(166–216)
		2 nd	190	178	185	177	186	188
		Half	(176–205)	(150–210)	(155–221)	(146–214)	(156–221)	(158–223)
	Slope	1 st	-0.17	-0.17	-0.16	-0.18	-0.18	-0.18
		Half	(-0.18 – -0.16)	(-0.19 – -0.15)	(-0.18 – -0.14)	(-0.20 – -0.17)	(-0.20 – -0.17)	(-0.19 – -0.16)
		2 nd	-0.16	-0.18	-0.17	-0.20	-0.19	-0.19
		Half	(-0.19 – -0.14)	(-0.23 – -0.13)	(-0.22 – -0.12)	(-0.25 – -0.14)	(-0.24 – -0.14)	(-0.24 – -0.14)
Relative High-Speed Distance (m · min ⁻¹)	Intercept	1 st	53	42	42	45	51	59
		Half	(44–63)	(28–63)	(27–65)	(28–72)	(33–78)	(39–90)
		2 nd	48	43	41	41	50	58
		Half	(37–62)	(24–76)	(23–75)	(21–79)	(28–91)	(32–104)
	Slope	1 st	-0.63	-0.68	-0.66	-0.63	-0.60	-0.59
		Half	(-0.66 – -0.60)	(-0.75 – -0.61)	(-0.73 – -0.59)	(-0.70 – -0.55)	(-0.67 – -0.53)	(-0.66 – -0.52)
		2 nd	-0.60	-0.64	-0.63	-0.68	-0.59	-0.61
		Half	(-0.69 – -0.52)	(-0.84 – -0.45)	(-0.83 – -0.43)	(-0.89 – -0.47)	(-0.79 – -0.40)	(-0.81 – -0.41)
Average Acceleration (m · s ⁻²)	Intercept	1 st	1.05	1.02	1.06	1.01	1.07	1.05
		Half	(1.00–1.10)	(0.92–1.13)	(0.95–1.18)	(0.89–1.14)	(0.96–1.19)	(0.94–1.17)
		2 nd	1.01	0.97	1.02	0.94	1.01	1.03
		Half	(0.95–1.08)	(0.83–1.13)	(0.87–1.19)	(0.79–1.12)	(0.86–1.17)	(0.88–1.20)
	Slope	1 st	-0.18	-0.17	-0.17	-0.19	-0.18	-0.17
		Half	(-0.18 – -0.17)	(-0.19 – -0.15)	(-0.19 – -0.15)	(-0.21 – -0.17)	(-0.20 – -0.16)	(-0.19 – -0.15)
		2 nd	-0.18	-0.17	-0.19	-0.19	-0.18	-0.19
		Half	(-0.20 – -0.15)	(-0.23 – -0.12)	(-0.24 – -0.13)	(-0.25 – -0.13)	(-0.24 – -0.13)	(-0.25 – -0.13)

across the majority of epochs in the first half ($ES = 0.62\text{--}1.63$). Additionally, AM also had greater TD peak match running demands than all other positional groups except for DM for most epochs in the second half ($ES = 0.70\text{--}2.08$). Further, AM, WD and WIN had greater HSD peak match running demands than CD and DM across first half epochs ($ES = 0.61\text{--}1.61$), with CD, DM and STR all lower than AM, WD and WIN in the second half ($ES = 0.60\text{--}1.61$). Peak match intensities for AveAcc were similar in both halves amongst all positional groups, except for STR which were lower than all positional groups, except for CD in the first ($ES = 0.63\text{--}1.02$) and second ($ES = 0.63\text{--}1.12$) halves. Differences between halves for each positional group at each intensity period are presented in Figure 2. Minimal differences were observed between halves for relative TD and HSD, with the peak relative TD covered by STR reduced in the second half at the 4–10 min windows ($ES = 0.60\text{--}0.89$), and similarly for HSD for the 7–10 min windows ($ES = 0.62\text{--}0.68$). However, several differences were observed for AveAcc, with STR and WD having lower peak AveAcc demands for all peak intensity periods in the second half ($ES = 0.62\text{--}0.84$), with similar observations made for DM at the 2–10 min windows ($ES = 0.61\text{--}0.81$).

DISCUSSION

The current study quantified the within- and between-halves and positional groups differences in peak match running demands for commonly assessed physical performance metrics. To provide further context, absolute measures of physical performance were also assessed. Both the absolute total and high-speed running demands were maintained between halves, however, the second half was on average ~ 3 min longer, reducing the relative distance covered for CD, DM, STR and WIN ($\sim 5\text{--}7 \text{ m} \cdot \text{min}^{-1}$). Conversely, the peak running demands of TD and HSD were similar between halves across all positional groups. Interestingly, while the total AveAcc was similar between halves for all positions, the peak AveAcc demands were reduced for DM, STR and WD in the second half. Taken together, the results demonstrate that the total and peak match demands of TD and HSD differ between positions but are maintained between halves. Separately, the peak AveAcc differ between positions and decline in the second half for some positions which provides direction for the prescription of training drills in conditioning for the high-energy demanding acceleration and deceleration actions.

While the quantification of match running volumes describes the global demands of match-play, it offers limited information to help guide conditioning and training drill prescription. The current peak match running demands ranged between $112\text{--}199\text{ m}\cdot\text{min}^{-1}$ for relative TD and $8\text{--}59\text{ m}\cdot\text{min}^{-1}$ for relative HSD, depending on position and epoch duration. These data are similar to those previously reported in the Australian A-League (TD: $\sim 115\text{--}205\text{ m}\cdot\text{min}^{-1}$, HSD: $\sim 10\text{--}65\text{ m}\cdot\text{min}^{-1}$) [13] and English Championship (TD: $\sim 115\text{--}197\text{ m}\cdot\text{min}^{-1}$, HSD: $\sim 13\text{--}61\text{ m}\cdot\text{min}^{-1}$) [14]. However, the AveAcc in the present study was considerably higher than that previously reported for the Australian A-League ($0.60\text{--}1.07\text{ m}\cdot\text{s}^{-2}$ vs $0.52\text{--}0.90\text{ m}\cdot\text{s}^{-2}$) [13]. Additional studies have assessed AveAcc in youth football players, however, differences in data filtering processes mean the data are not able to be directly compared [31]. As such, establishing a standardised methodology for assessing the AveAcc demands of match-play is warranted in future research.

The data demonstrated that AM have the greatest peak match running demands for relative TD covered, with CD and STR having the lowest. This is similar to previous data from the Australian A-League that identified CD as having the lowest peak match running demands [13], with all midfielders have the greatest and attackers have the lowest peak match running demands [14, 31]. Conflicting findings have been also reported on the peak relative HSD running demands, with the current study reporting that WD, WIN and AM have the greatest peak match high-speed running demands, whereas past data had reported that STR and WIN had the greatest demands [13] or that there were no positional differences [14]. Lastly, there is limited comparable data on the peak AveAcc demands, with previous research reporting that positional groups were similar, except for WD which had the greatest peak match running demands of AveAcc [13]. The current data presented similar findings, with the exception for STR, which demonstrated the lowest AveAcc demands. It is likely that the lack of consensus amongst literature around which positional group has the greatest peak match running demands for HSD and AveAcc is due to the differing demands associated with different playing formations or team tactics [32, 33]. While this data in the present study may not be reflective of all teams and competitions, it provides rationale for evaluating peak match running demands of competition relative to positional group.

Positional discrepancies in match running demands may reflect several contextual factors related to the performance of high-intensity efforts, which impact on a player's peak match running demands. High-intensity efforts are closely linked to critical parts of a match, such as scoring or defending goals [11, 12], and with more goal scoring opportunities in the second half [9, 10], there are likely more instances where high-intensity efforts are performed to impact upon the match result. As such, while absolute running demands of relative TD are lower, absolute and peak match running demands of HSD are maintained. Furthermore, ball in play time is lower in the second half [34] due to the more frequent game interruptions, and as a result the time spent in lower locomotor speed categories

increases [35]. Such a trend would result in a reduction in total physical output, but not impact on the peak match running demands. In comparison, any declines in peak AveAcc demands were position dependent, with AM, CD and WIN maintaining peak running intensities between halves, with DM, STR and WD declining. Past data has shown that the number of accelerations and decelerations performed in the second half reduces, with match related fatigue suggested as a contributing factor [36, 37]. While other factors such as self-imposed pacing strategies [3], or changes to team tactics [38] may also contribute. However, the collective data demonstrate that the peak AveAcc match demands are reduced in the second half for some positional groups.

While data is constrained by the limitation that it was only collected from a single professional football team, the assessment of positional peak match running demands is warranted to identify differences within a match, across all three assessed metrics. Hence, the application of such data should be to replicate these demands during training through the designing and implementation of position specific training drills. The methods presented by Delaney, Thornton [13] provide scope as to how to mathematically estimate peak match demands for a given duration using the data presented in Table 2. Exposure of players to peak match running demands in the initial phases of training will largely replicate the most difficult physical intensities of match-play, with peak demands typically greater in the first half. Conversely, structuring a training session to include match simulation drills at the end of a session may help develop the ability of players to perform at higher intensities during key tactical moments in the latter stages of a match. Further, while the underlying mechanistic properties behind differences in running performance between halves are multi-faceted, the understanding that reductions occur may help coaches evaluate implemented strategies aimed at mitigating said differences. Additionally, while not quantified in the present study, the technical and tactical demands of drills replicating match demands drills should also be considered, with drill dimensions, player numbers and drill constraints considerably impacting on both the technical and tactical demands, as well as physical demands [39]. Additionally, while peak match demands differed between halves for some positional groups, it is clear that players are regularly required to perform at or near peak match demands frequently across a match [19]. Hence, frequent performance at or near peak demands are suggested within training sessions. It is however important to note that peak physiological demands were unable to be quantified in the current study, with it possible that there may be a dissociation between peak physical and physiological demands, which would be useful for greater granularity when prescribing conditioning drills. Additionally, while not quantified in the current study, the variability of peak match running demands have previously been reported on, with the inherent variability of the measures worth considering [40].

Peak match running demands have emerged as a detailed method of assessing physical match performance that can aid in the

design and prescription of training stimuli. As such, providing context surrounding the acute changes in peak match running demands is crucial in preparing players for competition. Overall, the between half changes to peak match running demands are position dependent, indicating that the assessment of acute changes in peak match running demands should be assessed on a positional basis, as opposed to a team basis. Further, with past data demonstrating that peak match intensities occur at various stages throughout

a match [23], the timing of player exposure to these demands during training should be considered in developing training practices. Overall, the present study provides a framework in which to gauge the physical between half match performance of elite soccer players, in relation to peak match running demands.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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Warm-up optimization in amateur male soccer players: A comparison of small-sided games and traditional warm-up routines on physical fitness qualities

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ABSTRACT: The aim of this study was to compare the effects of small-sided soccer games (SSSGs) and traditional warm-up (TWU) routines on physical fitness qualities in soccer players. Following a between-subject, randomized design, amateur-level soccer players were assigned to a SSSG warm-up ($n = 10$; age: 19.3 ± 2.8 years) or TWU group ($n = 10$; age: 19.3 ± 2.4 years). Players completed multiple trials of 10-m and 30-m linear sprints, change-of-direction speed (CODS) tests, and countermovement jumps (CMJ) prior to and following the warm-up routine. Separate mixed ANOVAs were performed to assess group effects (SSSG vs. TWU), time effects within each group (pre- vs. post-warm-up), and their interaction for each physical fitness quality. No significant interaction effects were observed for any dependent variable. Significant improvements were evident between baseline and follow-up measurements for 10-m sprint time ($p = 0.002$, Hedges' g effect size [g] = 0.59) and CMJ variables (height: $p = 0.016$, $g = 0.20$; power: $p = 0.003$, $g = 0.19$; force: $p = 0.002$, $g = 0.14$) in the TWU group and for CODS performance time ($p = 0.012$, $g = 0.51$) and CMJ variables (height: $p < 0.001$, $g = 0.46$; power: $p = 0.002$, $g = 0.35$; force: $p = 0.001$, $g = 0.27$) in the SSSG warm-up group. Both SSSG and TWU protocols improved selected physical fitness qualities with SSSG more effective at improving CODS and CMJ performance, and TWU more effective at improving linear speed. Soccer coaches may choose between SSSG or traditional warm-up activities according to player needs and preferences; however, the superior effects of SSSG suggest it might offer greater benefits than TWU in preparing players for optimal physical output.

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INTRODUCTION

A warm-up helps to attain optimal performance [1] and reduces injury risk through various mechanisms such as increasing muscle temperature, nerve conductivity, metabolic reactions, blood flow, oxygen consumption, anaerobic energy provision, and force expression [2, 3] and inducing post-activation performance enhancement [4]. In addition, a warm-up may also provide an opportunity to mentally prepare players for upcoming tasks and induce positive psychological effects such as enhancing focus and self-confidence [1–3].

In soccer, warm-up protocols such as the FIFA 11+ prevention programme [5] or the Sportsmetrics Warm-up for Injury Prevention and Performance [6] commonly include running, static and dynamic stretching [7], neuromuscular activities for preventing injury [8], high-intensity and post-activation performance exercises [4], and drills with specific tactical objectives (e.g., pressing drills if a session's objective is defending) [9]. In this way, such warm-up protocols enhance performance in transitioning from less specific to more specific tasks, relative to the demands imposed during competitive

play. Given the frequent execution of high-intensity actions (e.g., sprinting, change in direction speed [CODS], jumping) in soccer [10, 11], specific warm-up activities may be key to optimizing the physical fitness qualities and skills of players most important for success [12]. In this sense, small-sided soccer games (SSSGs) used as a warm-up activity may optimize the specificity of player preparation as they closely resemble the demands of competition [13].

Though SSSGs have been extensively studied as a training method in soccer [13–16], evidence regarding their acute effects as a warm-up technique is scarce and heterogeneous in male soccer players, with benefits observed to physical fitness qualities (i.e., jump variables, CODS, repeated sprint performance) in amateur players over traditional warm-up (TWU) protocols (i.e. Premier League soccer club-based warm-up routine) reported in one study [9] but not shown in semi-professional players in another study [17]. Moreover, TWU (~23 min) are typically longer than SSSG when used in a warm-up protocol (~12 min) [9, 17], which indicates SSSG may offer useful practical benefits for administration of the warm-up phase in a time-efficient manner. In addition, existing research has only examined the effects of SSSG as a warm-up technique on physical fitness qualities in soccer players using 3 vs. 3 team configurations [9, 17] and without consideration of tactical constraints. In turn, SSSGs aimed at specific tactical elements with a greater number of players per team may induce a soccer-specific warm-up stimulation that better represents match-play and physically prepares players for upcoming demands [18, 19] than SSSGs tested to date.

Although some findings [9] on the effects of SSSGs used as a warm-up approach on physical fitness qualities in soccer are encouraging, due to the scarcity of literature and limited methodologies tested (i.e. 3 vs. 3 team configurations), we sought to compare the effects of SSSGs involving a greater number of players and targeting ball possession as a tactical consideration against a TWU. The focus on ball possession as a tactical element was included in our study given it has been popularized in the literature [9, 18, 19], and SSSGs aimed at this specific tactical element with a greater

number of players per team, such as 4 vs. 4 with 2 additional players on one team (i.e., 4 vs. 4 + 2) may induce a soccer-specific warm-up stimulation that better represents match-play. From a practical perspective, a 4 vs. 4 + 2 SSSG configuration allows more players in the squad to warm-up together simultaneously than SSSG with less players involved. Further, recent developments in warm-up strategies in soccer suggests that a short-duration (i.e., ~12 minutes) specific warm-up is as effective as a longer (i.e., ~20 minutes) warm-up in improving readiness to play a match [20] and physical fitness qualities (i.e., sprint and repeated sprint ability), and may induce lower perceived exertion [21, 22]. Accordingly, to increase the ecological validity of our study, a relatively short warm-up strategy was adopted (i.e., 12 min) for both warm-up protocols. Therefore, the aim of the study was to compare the effects of SSSGs and TWU routines on physical fitness qualities in soccer players. We hypothesized SSSGs as a warm-up approach would induce greater improvements in physical fitness qualities than a TWU in soccer players.

MATERIALS AND METHODS

Subjects

Based on a previously reported effect size for CODS ($ES = 0.8$) following a SSSG warm-up by Zois, Bishop [9] an *a priori* analysis using G*Power software (v.3.1.9.4, University of Kiel, Kiel, Germany) indicated that sample of 16 players would be required to obtain an $f = 0.4$ (large effect), and power = 0.80, with two groups and two measurements. Consequently, twenty-four male players volunteered to take part in the study. The inclusion criteria for the study involved: attendance at the familiarization session and the absence of any major injury in the lower-limbs in the previous 6 months or any other recent injury. Three players did not complete the familiarization session and one player was injured during training prior to data collection. Accordingly, 20 players (age: 19.3 ± 2.6 years; height: 162.3 ± 6.0 cm; body mass: 60.6 ± 8.2 kg) from an amateur India 2nd division league soccer club completed the study (Table 1). An online randomization tool (www.randomizer.org) was used to

TABLE 1. Demographic and aerobic capacity variables between the traditional warm-up (TWU) and small-sided soccer game (SSSG) warm-up groups.

Variables	Overall (n = 20)	TWU Group (n = 10)	SSSG Group (n=10)	p-value
			Mean $\pm$ SD	
Age (years)	19.3 ± 2.6	19.3 ± 2.4	19.3 ± 2.8	1.00
Height (cm)	162.3 ± 6.0	161.5 ± 4.6	163.1 ± 7.4	0.59
Body mass (kg)	60.6 ± 8.2	62.1 ± 8.5	59.1 ± 8.1	0.79
Yo-Yo IR1 distance (m)	908 ± 246	976 ± 202	840 ± 277	0.23
VO ₂ max _{predicted} (ml/kg/min)	44.0 ± 2.1	44.6 ± 1.6	43.5 ± 2.4	0.23

Note: p-values derived from separate independent t-tests showing groups to be similar across variables; abbreviations ordered alphabetically; SD: standard deviation; VO₂max_{predicted}: predicted VO₂max; Yo-Yo IR1: Yo-Yo Intermittent Recovery Level 1.

allocate players to the SSSG ($n = 10$) and TWU ($n = 10$) (Table 1). The players were informed about the study details and risks of participation before providing written informed consent. The study was approved by the Departmental Research Committee of Lakshmibai National Institute of Physical Education and the protocol conformed to the Declaration of Helsinki (1964, updated in 2013).

Procedure

One familiarization session was conducted a week prior to data collection. Standing height, age, and Yo-Yo intermittent recovery level 1 tests scores were recorded on the same day as familiarization. The temperature, humidity, and wind velocity upon commencing the testing session were 19° C, 84%, and 4 km/h respectively. Players were asked to refrain from any strenuous activity and alcohol consumption for 24 h and eating for 3 h prior to testing.

A between-subject, randomized design was used to compare the effects of SSSGs with a TWU on 10-m and 30-m linear sprint, CODS, and countermovement jump (CMJ) performance. The study was conducted during the start of the pre-season. Players were provided with a day of rest prior to data collection, and assessed on a single day between 9:00 and 11:00. Upon arrival for testing, players underwent body mass measurement, followed by very light jogging (~60% of self-estimated maximum heart rate intensity) for 5 min, baseline testing, the warm-up protocol (i.e., TWU or SSSG) for 12 min, and follow-up testing after 5 min of passive standing (i.e., to facilitate the resynthesis of high-energy phosphate pools [23, 24]) (Figure 1). The players wore the same football shoes in all the assessments, carried out on natural soccer turf, led by the same assessor.

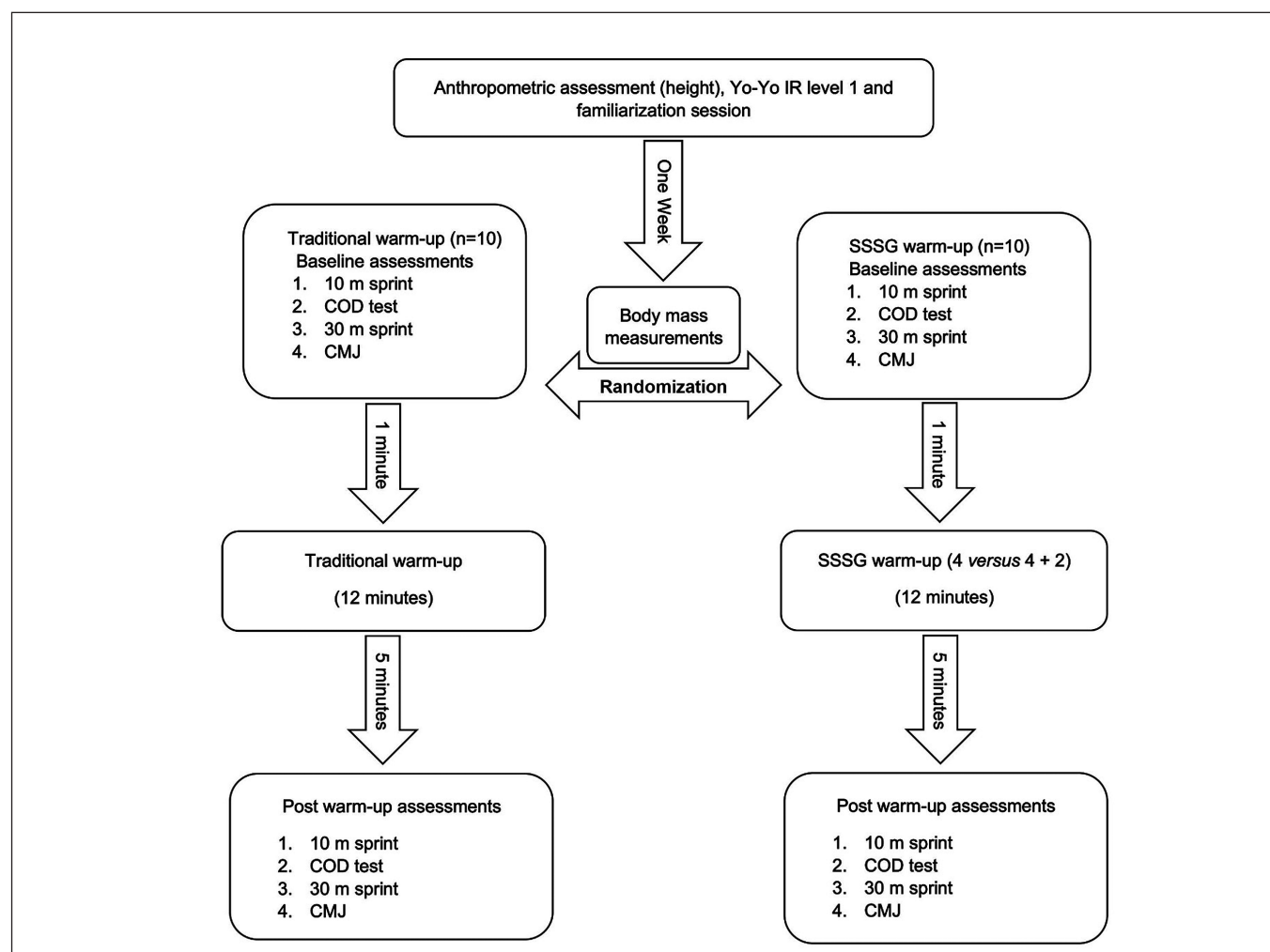


FIG. 1. Schematic of the study design.

Note: Yo-Yo IR level 1: Yo-Yo Intermittent Recovery Test level 1; SSSG: small-sided soccer game; COD: change-of-direction; CMJ: countermovement jump.

Warm-up protocols

Traditional warm-up

Players completed a series of dynamic stretching exercises across 15 m before jogging back at a self-selected speed to the starting line. In this fashion, players completed two sets of adductor (i.e., internal rotation), abductor (i.e., external rotation), hamstring (i.e., single stiff leg forward bending stretch), gluteal (i.e., hip flexion and extension), and ankle-oriented (i.e., ankle rotation) dynamic stretching exercises. Thereafter, players completed five 15-m sprints at 60% of maximal self-estimated effort (i.e., 100% would represent the perceived maximal speed in a 15-m sprint), three sprints at 80% of maximal self-estimated effort, two sprints at 90% of maximal self-estimated effort, and a final sprint at maximal effort. After each sprint, players jogged back at a self-selected speed to the starting line.

Small-sided soccer game warm-up

The SSSG warm-up protocol consisted of a 12-min match on a 15-m $\times$ 15-m pitch. The SSSG focused on ball possession with a 4 vs. 4 plus 2 neutral players configuration adopted given its common use in soccer [25, 26] (Figure 2). In addition, SSSGs aimed at ball possession as a tactical element and with a greater number of players per team (i.e., 4 vs. 4 + 2) may induce a soccer-specific warm-up stimulation that better represents match-play and physically prepares players for upcoming demands than configurations (i.e., 3 vs. 3) examined previously [9, 17].

Players were randomly distributed to teams and were instructed to keep possession of the ball for as long as possible. Two licensed soccer coaches supervised the SSSGs. The team in possession of the ball was supported by two neutral players (i.e., replaced after each set, with all players acting as neutral players at some point) to keep possession of the ball, meaning play comprised of 6 vs. 4 players to create a numerical advantage for one team. Six sets of exercise were performed in the SSSG warm-up, with each set consisting of 90 s of active play followed by 30 s of active recovery. During the active recovery, players completed the same dynamic stretches as completed in the TWU group. One of the coaches provided verbal cues (e.g., 'keep moving', 'don't lose the ball', 'make the defenders move') to the team in possession of the ball. A second coach provided verbal cues (e.g., 'press', 'win the ball', 'don't let them play') to the defending team. The two coaches timed each SSSG set and active recovery, and ensured a replacement ball was always available.

Physical fitness test battery

Linear sprint tests

A 10-m (ICC = 0.79) and a 30-m (ICC = 0.96) linear sprint test was conducted 5 min and 15 min, following completion of the warm-up protocol respectively. A timing system consisting of two pairs of single-beam photocells (Cronox, Madrid, Spain) was positioned at a height of 0.6 m above ground level and players started 0.5 m behind the first photocell with their preferred foot forward on a marked

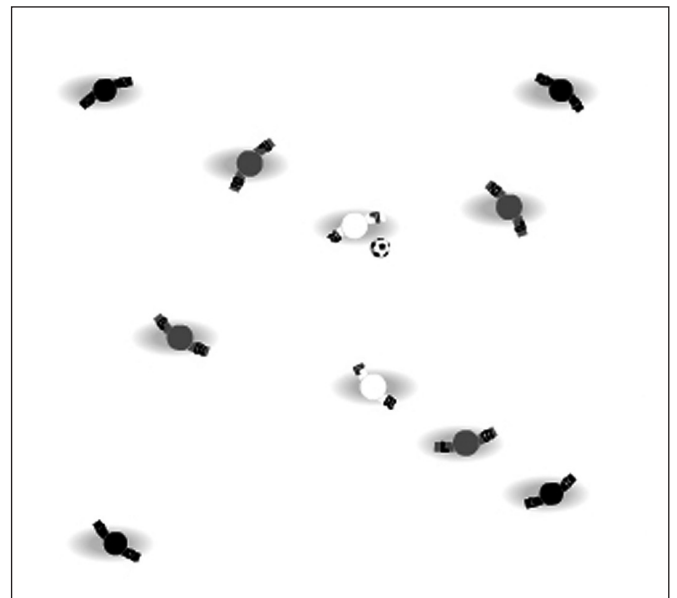


FIG. 2. The setup of the small-sided soccer games following a 4 (black) vs. 4 (grey) + 2 (white) neutral players configuration on a 15-m $\times$ 15-m pitch. The white players supported the team in possession of the ball.

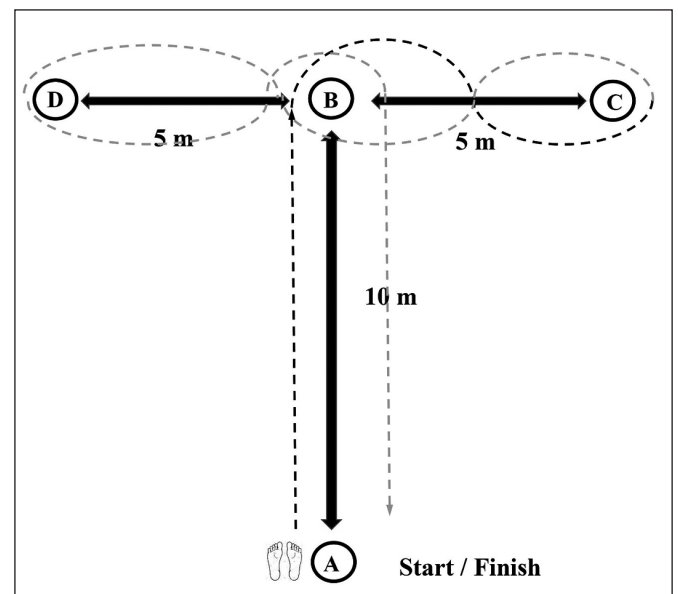


FIG. 3. The configuration of the modified version of the agility t-test was used to assess change-of-direction speed. Cones at a height of 0.3 m were placed at points A, B, C, and D with players being instructed to sprint from A to B, perform a 90° turn from cone B towards cone C, then perform a 180° turn at cone C towards cone B, before performing a turn at cone B towards cone D, then performing a 180° turn at cone D towards cone B, and finally returning to the start/finish line. The players were required to weave around the cones without touching them. Trials were discarded if the cones were displaced while changing direction with players being required to repeat the trial after 1 min of passive standing rest. Note: black line denotes primary turns, and grey line denotes secondary turns.

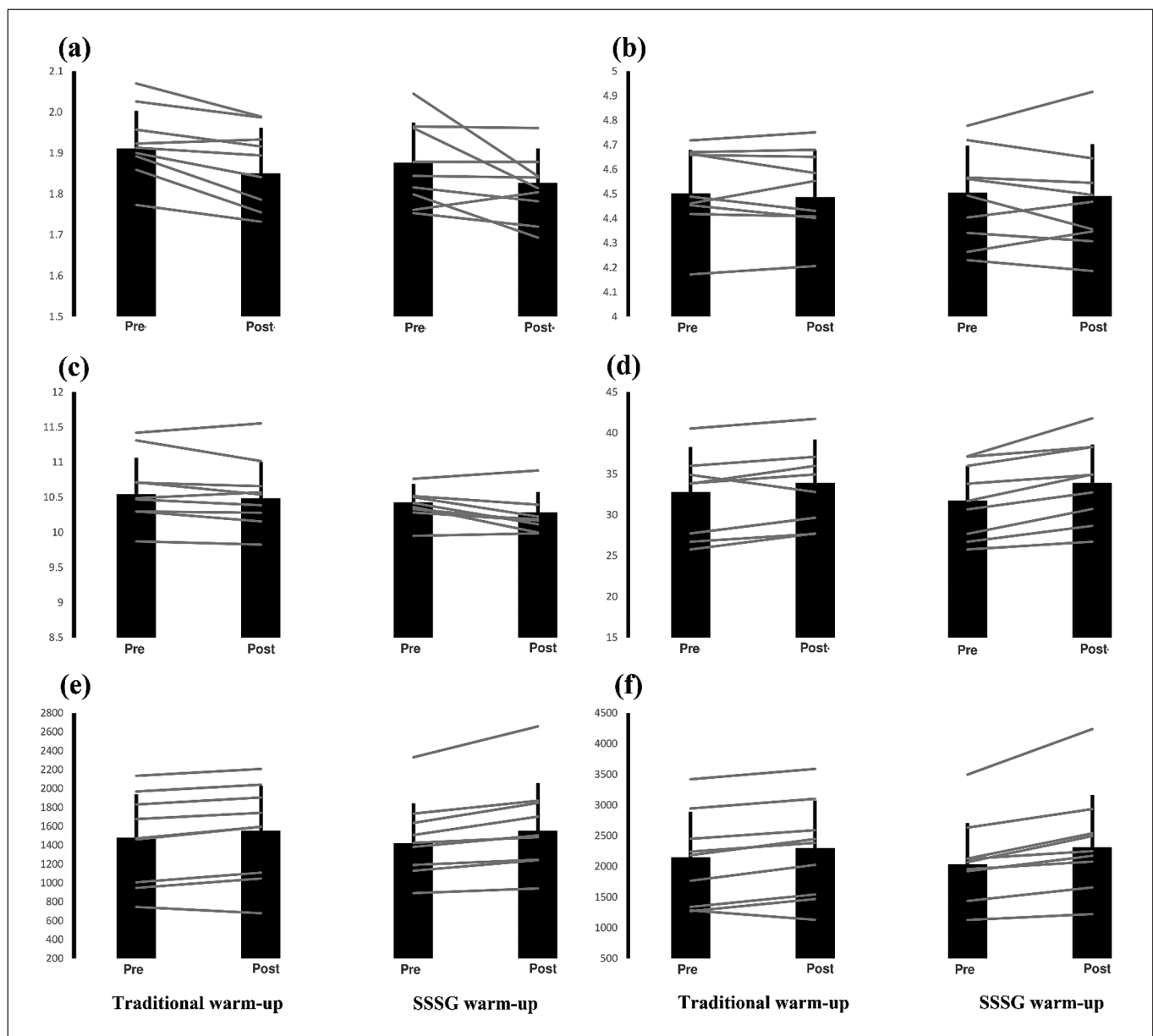


FIG. 4. Mean (column) $\pm$ standard deviation (error bar) along with individual responses (grey lines) for (a) 10-m linear sprint time [s], (b) 30-m linear sprint time [s], (c) change-of-direction speed test time [s], (d) countermovement jump height [cm] (e) countermovement jump force [N] and (f) countermovement jump power [W] prior to and following a traditional warm-up and small-sided soccer game (SSSG) warm-up protocol.

line. Two trials were conducted for each sprint test, with a 1 min passive standing rest between trials. The fastest trial was selected for analysis in each sprint test.

Change-of-direction speed test

A CODS test was conducted 8 min following completion of the warm-up protocol using a modified version of the the agility T-test (ICC = 0.91) [27], to replicate soccer-specific CODS demands (Figure 3). A timing system with one pair of single-beam photocells (Cronox, Madrid, Spain) was placed at a height 0.6 m above ground level at the start/finish line. Players started 0.5 m behind the start/finish line in a standing position with their preferred foot forward.

Two trials were conducted with 1 min of passive standing rest between trials and the fastest trial selected for analysis.

Countermovement jump

A CMJ test with the hands on the hip was conducted 20 min following completion of the warm-up protocol. Players were instructed to jump maximally following a countermovement with a self-selected magnitude of knee flexion. Height (CMJ_{height}), force (CMJ_{force}) and power (CMJ_{power}) (all ICC = 0.96) generated during the CMJ were measured with a validated (vs. force plate, jump height: $r = 0.99$; jump power: $r = 0.85$) IOS application, My Jump 2, installed on an Apple iPad 8th generation (Apple Inc., California, USA) with

a 120-Hz high-speed camera at a quality of 720 p. The camera was directed as low as possible facing each player in the frontal plane ~2 m away to best record jump performance. Two trials were performed by each player with a recovery period of 1 minute between trials. The highest value for each variable was selected for analysis.

Statistical analysis

Analyses were conducted using IBM SPSS version 20.0.0 (IBM, New York, USA). The normality of all data was verified using the Shapiro-Wilk test. Data are presented as mean $\pm$ standard deviation (SD). A two (baseline vs. follow-up testing) $\times$ two (TWU vs. SSSG warm-up) mixed ANOVA was used to analyze the collected data. In addition, paired (within-group comparisons) and independent (between-group comparisons) t-tests were used for post-hoc analyses with Bonferroni adjustments applied. The percentage change score for each variable in each group was calculated using the equation: $[(\text{mean}_{\text{post}} - \text{mean}_{\text{pre}}) / \text{mean}_{\text{pre}}] \times 100$. Effects sizes were calculated as partial eta squared (η_p^2) for interaction and main effects in each ANOVA and as Hedge's g to assess changes between baseline and follow-up testing in each group. The magnitude of effects for $\eta_p^2(p)$ was interpreted as small (< 0.06), medium (≥ 0.06 – 0.13), and large (≥ 0.14) [29], while Hedge's g was interpreted as trivial (< 0.2), small (0.2 – 0.6), moderate (> 0.6 – 1.2), large (> 1.2 – 2.0), very large (> 2.0 – 4.0) and extremely large (> 4.0) [30]. Statistical significance was set at $p \leq 0.05$.

RESULTS

The mean $\pm$ SD for each dependent variable is shown in Table 2, with individual data presented in Figure 4. Statistical outcomes for comparisons in each dependent variable are also shown in Table 2. No significant baseline ($p = 0.41$ – 0.86) differences were observed between the TWU group and the SSSG group (i.e., independent t-test) in any of the dependent variables further supporting the matching of groups regarding physical fitness qualities.

Separate 2×2 mixed ANOVAs revealed no significant group effects ($p = 0.29$ – 0.99) or interaction effects (time $\times$ group) ($p = 0.08$ – 0.95) for any dependent variable. However, significant time effects were observed in 10-m sprint time ($p = 0.001$, $\eta_p^2 = 0.46$), CODS test time ($p = 0.003$, $\eta_p^2 = 0.39$) and CMJ variables (CMJ_{height}, $p = < 0.001$, $\eta_p^2 = 0.67$; CMJ_{power}, $p = < 0.001$, $\eta_p^2 = 0.65$; CMJ_{force}, $p = < 0.001$, $\eta_p^2 = 0.68$). Post-hoc paired sample t-tests revealed significant improvements in 10-m sprint time ($p = 0.002$, $g = 0.59$) and CMJ variables (CMJ_{height}, $p = 0.016$, $g = 0.20$; CMJ_{power}, $p = 0.003$, $g = 0.19$; CMJ_{force}, $p = 0.002$, $g = 0.14$) in the TWU group. On the other hand, significant improvements in CODS test time ($p = 0.012$, $g = 0.51$) and CMJ variables (CMJ_{height}, $p = < 0.001$, $g = 0.46$; CMJ_{power}, $p = 0.002$, $g = 0.35$; CMJ_{force}, $p = 0.001$, $g = 0.27$) were observed in the SSSG warm-up group (Table 2).

TABLE 2. Statistical comparisons for changes in physical fitness qualities between traditional warm-up and small-sided soccer games (SSSG) warm-up protocols in soccer players.

Variable	Traditional warm-up group (n = 10)				SSSG warm-up group (n = 10)				Main time effect	Time $\times$ group
	Baseline	Follow-up	% Δ	p -value [g] Magnitude	Baseline	Follow-up	% Δ	p -value [g] Magnitude	p -value [η_p^2] Magnitude	p -value [η_p^2] Magnitude
	Mean $\pm$ SD	Mean $\pm$ SD			Mean $\pm$ SD	Mean $\pm$ SD				
10-m sprint time (s)	1.91 $\pm$ 0.09	1.85 $\pm$ 0.11	-3.2%	0.002* [0.59] Moderate	1.88 $\pm$ 0.10	1.83 $\pm$ 0.09	-2.6%	0.076 [0.51] Moderate	0.001* [0.460] Large	0.661 [0.011] Small
30-m sprint time (s)	4.50 $\pm$ 0.18	4.49 $\pm$ 0.19	-0.3%	0.466 [0.07] Trivial	4.51 $\pm$ 0.19	4.49 $\pm$ 0.21	-0.3%	0.644 [0.06] Trivial	0.415 [0.037] Small	0.951 [< 0.001] Small
CODS time (s)	10.55 $\pm$ 0.52	10.49 $\pm$ 0.52	-0.6%	0.157 [0.11] Trivial	10.43 $\pm$ 0.26	10.28 $\pm$ 0.29	-1.4%	0.012* [0.51] Moderate	0.003* [0.392] Large	0.171 [0.101] Medium
CMJ _{height} (cm)	32.8 $\pm$ 5.5	33.9 $\pm$ 5.30	3.4%	0.016* [0.20] Small	31.7 $\pm$ 4.2	33.9 $\pm$ 4.7	6.8%	< 0.001* [0.46] Small	< 0.001* [0.671] Large	0.078 [0.162] Large
CMJ _{power} (W)	2149 $\pm$ 737	2301 $\pm$ 769	7.1%	0.003* [0.19] Trivial	2030 $\pm$ 674	2310 $\pm$ 850	13.8%	0.002* [0.35] Small	< 0.001* [0.654] Large	0.099 [0.144] Large
CMJ _{force} (N)	1479 $\pm$ 458	1552 $\pm$ 478	4.9%	0.002* [0.14] Trivial	1419 $\pm$ 421	1551 $\pm$ 504	9.3%	0.001* [0.27] Small	< 0.001* [0.676] Large	0.098 [0.145] Large

Note: abbreviations ordered alphabetically; CODS: change-of-direction speed; CMJ: countermovement jump; g : Hedges' g effect size; η_p^2 : partial eta squared; SD: standard deviation; % Δ : percentage change score between baseline and follow-up measures; *: significant difference between baseline and follow-up measures; #: significant main time effect.

DISCUSSION

The aim of this study was to compare the effects of TWU and SSSG as warm-up approaches on physical fitness qualities in soccer players. Results revealed both warm-up protocols induced improvements in physical fitness qualities deemed important in soccer. However, moderate improvement in 10-m linear speed (3.2%) and small to trivial improvement in CMJ performance (3.4–7.1%) was observed following TWU, while moderate improvement in CODS (1.4%) and small improvement in CMJ performance (6.8–13.8%) was observed following SSSGs. Therefore, the present findings confirm SSSG can be used as a warm-up strategy to acutely improve important physical fitness qualities in soccer players.

Our findings suggest warm-up strategies, in the form of a TWU or SSSG, improve various physical fitness qualities in soccer players. In agreement with our results, previous research has shown various warm-up strategies, such as TWU, 3 vs. 3 SSSG, long specific, short specific, and 5-repetition maximum leg press to improve physical fitness qualities, including linear sprint, vertical jump, reactive agility, and repeated sprint ability in various samples of soccer players [9, 17, 21, 22]. Both warm-up protocols examined in this study likely produced positive acute effects on physical fitness qualities due to various physiological mechanisms, but namely a rise in body temperature which subsequently enhances muscle metabolism [31] as well as increases muscle fiber contractile performance [32] and conduction velocity [33]. In this regard, a 1°C increase in muscle temperature enhances power output and can improve exercise performance such as sprinting, jumping, and maximal strength during knee extension between 2–5% [34–36]. Relatedly, warm-up protocols intended to increase muscle temperature have also been shown to be positively related to movement velocity during 20-s maximal efforts on isokinetic cycle ergometers [35] and relative work rate during cycling [37]. Furthermore, an elevation in oxygen uptake kinetics [38] following dynamic warm-up protocols may enhance the functioning of the cardiovascular system (e.g., increased systolic volume). Consequently, the multidimensional acute benefits of different warm-up protocols likely underpin the benefits we observed for various physical fitness qualities in soccer players.

While both warm-up protocols improved physical fitness, we noted a moderate improvement in 10-m sprint time only in the TWU group, probably attributed to the specificity of the TWU protocol to linear sprinting. Indeed eleven 15-m linear sprints at different intensities were performed in the TWU group, which may have promoted neuromuscular activation and coordination of muscles recruited specifically across 10-m sprints [39]. In support of this notion, literature suggests warm-up activities should be chosen on the degree of their specificity relative to the exercise they precede [3, 39]. In turn, van den Tillaar, Lerberg [22] suggested the mere execution of an extended generalized warm-up did not constitute a sufficient stimulus to improve maximal linear sprint performance, but instead recommended a targeted approach of specific activities that resemble the nature of subsequent performance. Accordingly, the significant improvement in

10-m linear sprint speed in the TWU group but not in the SSSG warm-up group could be explained by the absence of specific linear sprinting activities being employed in the ad hoc match-play involved in the SSSG. In a similar vein, the lack of any improvement in 30-m sprint speed in both the TWU and SSSG groups could be due to the insufficient specificity of the stimulus with neither performing sprints of this distance in the respective warm-up protocols. Similar to our findings, Zois, Bishop [9] reported no significant improvement in 20-m linear sprint performance after a SSSG warm-up following a 3 vs. 3 configuration. Therefore, from a practical perspective, the collective evidence suggests soccer-specific linear sprints (e.g., 10–30 m) should accompany SSSG when used as a warm-up to gain maximal benefits, such as during the active intra-set recovery period interspersed throughout SSSG.

In contrast to 10-m linear sprint performance, only the SSSG warm-up group experienced significant positive improvements in CODS. In line with the principle of specificity discussed for our findings regarding discrepancies in the effects of each warm-up on 10-m linear sprint speed, players executed several changes-of-direction with or without the ball during the SSSG warm-up but not during the TWU. Activity patterns during the SSSG may have activated muscles required for effectively changing direction (e.g., adductor magnus, hamstrings, gluteus maximus, quadriceps) [40] and, in the process, enhanced CODS. Indeed, a meta-analysis indicated that SSSG training improve CODS in team sports athletes such as soccer, handball, rugby, volleyball, and Australian football players [41]. Furthermore, a small pitch area, such as the 15-m × 15-m pitch we utilized, has been suggested to increase the pressure placed on players on offence given there is less space to evade defenders, necessitating fast multi-directional movements to maintain possession [15]. Indeed, Zois, Bishop [9] observed a similar acute improvement (3.8%) in reactive agility speed following a SSSG warm-up, which exceeded the benefit (0.9%) of a TWU consisting of general activities such as butt-kicks, high-knees, and body-weight squats, specific movements such as lateral skipping, back and forth sprinting, and CODS movements, and ball control activities such as dribbling, passing, and run-through. Therefore, the collective evidence suggests SSSG warm-ups are superior to TWU in promoting benefits for CODS.

Our study also demonstrated improvements in CMJ performance with both warm-up protocols. Although no group by time interactions were noted for CMJ variables, the SSSG warm-up induced a two-fold increase in CMJ performance (6.8% CMJ_{height}, 13.8% CMJ_{power}, 9.3% CMJ_{force}) compared to the TWU (3.4% CMJ_{height}, 7.1% CMJ_{power}, 4.9% CMJ_{force}). Our results confirm those reported by Zois, Bishop [9] who observed a 3 vs. 3 SSSG warm-up increased CMJ_{height} (6%) more than a traditional team-sport warm-up (< 1%) among amateur male soccer players. Similar findings were also observed among handball players, where a small-sided games based warm-up routine elicited better performance in CMJ than the TWU [42]. The greater improvement in CMJ performance with SSSG warm-up protocols compared to TWU protocols could be attributed to an intensity-dependent relationship [43]

whereby warm-up protocols performed at higher intensities have been shown to elicit greater positive effects on jumping performance (i.e., drop jump, CMJ, and squat jump) among volleyball players [43] and basketball players [44]. In this sense, the SSSG warm-up likely required players to perform more frequent high-intensity efforts, including jumps, while undertaking different unpredictable match scenarios compared to the planned TWU protocol. Indeed, the SSSG involved some unplanned jumping actions potentially leading to a post-activation phenomena (e.g., increased muscle activation) [43] that aided subsequent jumping performance during testing as previously demonstrated in rugby players [45].

While the present study offers novel insight into the efficacy of different warm-up protocols in soccer, some limitations should be acknowledged. Firstly, useful physiological measurements such as heart rate, core temperature, oxygen consumption, and blood lactate concentration were not able to be measured and therefore prevented definitive physiological reasoning from being provided to explain our findings across the different warm-up protocols. Secondly, given we examined amateur soccer players, the results cannot be simply extrapolated to players competing at higher levels due to potential differences in physical fitness and responses to warm-up activities across playing levels. Additionally, we did not examine other task constraints (e.g., touch limitation, pitch size) which could potentially affect the outcomes [46]. Finally, although the gold standard randomized, crossover design was not permissible to use in our study given players were not available for repeated assessments, we examined groups that were closely matched across various demographic and physical fitness variables following a between-groups design. Nevertheless,

future studies on this topic should aim to implement randomized, crossover study designs as this approach better accounts for the inter-individual variability across players.

CONCLUSIONS

In conclusion, both traditional and SSSG warm-up protocols improved selected physical fitness qualities, with SSSG more effective at improving CODS and CMJ performance, and TWU more effective at improving linear speed in soccer players. Soccer coaches may choose between SSSG or TWU activities according to player needs and preferences; however, the superior effects of SSSG on CODS and CMJ variables suggests it might offer greater benefits than TWU in preparing players for optimal physical output. Furthermore, coaches and practitioners could supplement the SSSG warm-up with short linear sprints to ensure linear speed is also optimized. Future studies are encouraged stemming from our work to assess whether technical abilities and tactical behaviors can be preferentially improved with specific warm-up approaches in soccer.

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Conflict of interest declaration

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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**DOFINANSOWANO
ZE ŚRODKÓW
BUDŻETU PAŃSTWA**

**Program Ministerstwa Nauki
i Szkolnictwa Wyższego**
Rozwój Czasopism Naukowych

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**DOFINANSOWANIE
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109 600,00 zł**

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