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DETERMINANT FACTORS OF ATTACK EFFICACY IN HIGH-LEVEL MEN'S VOLLEYBALL: WHAT DOES DISTINGUISH THE MIDDLE-ATTACKER PERFORMANCE?

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Abstract:

This study aimed to identify determinant factors of attack efficacy considering the effects of reception, attack tempo, attack performance, setting type and attack type. Firstly, 19,454 offensive actions of complex I of the Brazilian Volleyball Men's Super League were considered and analyzed separately from the middle, wing, and opposite attacker standpoints. The middle attack was the most effective, so the 5,259 offensive actions were analyzed considering the setting type and the attack direction. The independent variables were the quality of reception, type and direction of attack, whereas attack performance was the dependent variable. We found that the middle attack efficacy was related to excellent receptions, right tempo and left tempo (near the setter), and power attack. The results can afford coaches with the key information for better training plan designs and preparation for competition.

Keywords: *factors in sport performance, tactics, performance, attack efficacy*

Introduction

Game analysis is necessary to detect patterns and regularities in the behavior of the players (McGarry, Anderson, Wallace, Hughes, & Franks, 2002), information that can be used to optimize training processes and team performance (Lames & McGarry, 2007; McGarry, 2009). Specifically, in volleyball, several studies have been developed to understand the factors that mostly contribute to team performance and the victory of the game (Peña, Rodriguez-Guerra, Buscà, & Serra, 2013). In this context, the attack is an action considered critically related to winning the set and the game (Costa, Ferreira, Junqueira, Afonso, & Mesquita, 2011; Monteiro, Mesquita, & Marcelino, 2009).

Considering the deterministic structure of volleyball game, with the number of touches constraint and the non-invasive character (Mesquita, 2005), researchers are devoted to understanding what game patterns afford the achievement of superior attack efficacies (e.g., Afonso, Esteves, Araújo, Thomas, & Mesquita, 2012; Marcelino, Mesquita, & Sampaio, 2011; Palao, Santos, & Ureña, 2004). However, the studies have shown high dependency of the attack efficacy and performance on previous actions, such as reception (João & Pires, 2015, Silva, Lacerda, & João, 2014b), setting type (Afonso, Mesquita, Marcelino, & Silva, 2010, Afonso, et al., 2012), attack tempo (Bergeles & Nikolaidou, 2011), and the attack type (Costa, et al., 2011).

The effect of reception is mostly recognized as a significant predictive factor of scoring points during an attack (Conti, et al., 2018, Costa, et al., 2017). For the reception effect, the relationships between reception and attack options are considered, which are classified as: a) all available attack options; b) quick attacks are possible, but they are more difficult to perform and some attack combinations are inhibited; and c) slow attack and off-court lifts are the most possible (Hurst, et al., 2016). High-quality receptions are associated with better setting conditions and, consequently, better conditions for the attack, which could be observed in the availability of all attack players (Afonso, & Mesquita, 2011; Barzouka, Nikolaidou, Malousaris, & Bergeles, 2009; Silva, Lacerda, & João, 2014a), fast attack tempos (Palao, Santos, & Ureña, 2007), and powerful attacks (Costa, et al., 2011, 2017). These favorable conditions are consequently related to an increased likelihood of scoring a point (Costa, et al., 2011, Peña, et al., 2013).

The attack tempo and the attack type are also significant predictors of attack efficacy (Conti, et al., 2018; Costa, et al., 2017). The attack tempo considers the relationship between the attacker and setting and is classified as: a) first tempo attack, when the attacker is in the air or jumps during or quickly after the setting; b) second tempo attack, when the attacker takes two steps after lifting for setting; and c) third tempo attack, when the attacker takes three or more steps after lifting for setting (Costa, et al., 2012). In addition, the type of attack considers the relationship between force implemented to the ball and the technique. Therefore, the type of attack is classified as: a) powerful attack, when the attack is performed powerfully using the palm of the hand in a downward trajectory; b) placed attack, when the attack is performed using the palm of the hand but with power control, directing the ball to a defensive vulnerable location; and, c) tip, when the attack is performed using the fingertips, directing the ball to a defensive vulnerable location (Costa, et al., 2011).

Considering the emergent patterns of the game, the effectiveness of the offensive organization is mainly based on a higher number of attack options, faster attack tempos, and powerful attacks (Mesquita, Palao, Marcelino, & Afonso, 2013, Silva, Marcelino, Lacerda, & João, 2016). These variables have been recognized as the ones with the most influence on the efficacy of complex I (Lobietti, Cabrini, & Brunetti, 2009; Paulo, Zaal, Fonseca, & Araújo, 2016).

Studies have shown that faster attacks (first and second tempos) are associated with winning attack points, which is not observed in slower attacks (third tempo) (Garcia-de-Alcaraz, Ortega, & Palao, 2017). This association could be explained by the difficulty in the organization of the opponent's defensive system, particularly blocking actions (Bergeles & Nikolaidou, 2011; Pinto, Vale, & Vicente, 2018). Moreover, the powerful and technical attacks have been the most used during games (Conti, et al., 2018; Costa, et al., 2017). The powerful attacks (i.e., attacks that privilege power) are defined in opposition to off-speed attacks (i.e., slower attacks privileging placement instead of power) (Castro, Souza, & Mesquita, 2011). In this context, empirical evidence has shown that scoring is associated with powerful attacks, and its use is related to the situational constraints related to the opponent's defensive organization (Klaricic, Grgantov, & Jelaska, 2018).

Considering the importance of faster attack tempos and diversified offensive options for attack efficacy, the performance of the middle-attacker becomes of great interest since this is a player that could hit the fastest attack tempos (i.e., first tempo) (Hileno, Garcia-de-Alcaraz, Buscà, Salas, & Camerino, 2018; Millán-Sánchez, Rábago & Epa, 2019). For example, Millán-Sánchez, Parra-Royón, Benítez, and Espa (2020) found that in male teams, the side-out performance improved when the setter moved at least one meter less than 30º. Thus, middle-attacker availability constitutes an outstanding variable when considering the dynamic nature of volleyball (Afonso, et al., 2010). Curiously, only a few studies have examined the performance of this player when considering attack efficacy (Peiró, et al., 2016). For example, Costa et al. (2016) analyzed the offensive game performed by the middle attacker in complex I (i.e., the attack organization after the opponent's service [Afonso & Mesquita, 2007]), and found that the middle attacks occurred mostly after high-quality receptions, being the most frequent attack scoring point as well as the most powerful one. Moreover, the authors highlighted that the middle attack had a positive effect on the winning score since it decreased the chances of the opponents' defense due to the reduced time for defensive organization. Despite the importance of such findings, little is known about the middle-attacker's performance. Indeed, there is a lack of knowledge concerning the type of setting (i.e., right tempo, left tempo, back tempo, and seven) specifically performed to the middle-attacker. The study of setting type and the attack type and its relationship with the attack efficacy performed by the middle-attacker is of utmost importance since it could provide us with more evidence about the most effective strategies for scoring a point when analyzing the game played by the middle-attacker.

Therefore, this study had two objectives. The first one was to identify the predictive factors of the attack efficacy on the side-out (transition I). We analyzed the side-out because the higher efficacy in side-out is related to the victory in sets, games, and the final position in championships (Ugrinowitsch, et al., 2014). The second goal was to analyze the middle-attacker's performance, considering the setting type and the attack direction that could be performed by this player.

For this objective, we considered the effects of reception, attack tempo, attack performance, setting type, and attack type.

Methods

Sample

A total of 19,454 offensive actions observed in complex I (i.e., side-out – the attack organization after the service of the opposite team) (Afonso & Mesquita, 2007; Costa, et al., 2011) were obtained from 142 matches of the 2015 Brazilian Volleyball Men's Super League. This total of matches represents 94% of the matches and covers from 22 to 26 matches observed of each team, aiming at data homogeneity. However, since the first attack tempo increases the possibilities of score points (Costa, et al., 2017, 2018), particularly in complex I, the sample was composed of 5,259 first tempo attack actions.

Variables

For all attack actions performed for the middle-attackers, the effects of the variables of reception, attack tempo, attack performance, setting type, and attack type were analyzed. To analyze specifically the attack efficacy of the middle-attacker, the variables particularly related to this player were further considered, namely the setting type and some of the variables of the attack type (i.e., the attack direction that could be performed by this player: hard-driven parallel attack to zone 6, hard-driven diagonal attack to zone 1 and zone 5, and placed attack).

Effects of reception: this variable considers the quality of reception and its influence on the attack organization. In order to analyze the quality of reception, the instrument of Eom and Schutz (1992) was adapted. The following rating scale was determined:

- Poor quality reception (C): leaves no possibility of an organized attack, with only wing attackers available for the attack. Since we investigated the middle-attacker, receptions C were not analyzed in this study;
- Moderate quality reception (B): offers the possibility of an organized attack but not all the attackers are available for the attack organization; more specifically, inhibits quick attacks;
- Excellent quality reception (A): gives the opportunity of an organized attack, with all the attackers available for the attack organization.

Attack tempo: corresponds to the timing of an attack action as regards the temporal relationship between the attacker, the setter, and the ball (Selinger & Ackermann-Blount, 1986). The adapted categories defined by Afonso et al. (2010) are presented below, but since the aim of the study was to investigate the middle-attacker, we analyzed only the first tempo attack.

- First tempo attack: the attacker takes off during or slightly after the setting;
- Second tempo attack: the attacker takes two or three steps after the setting;
- Third tempo attack: the attacker waits until the ball reaches the peak of the ascending trajectory, and only then starts a three-step approach.

Attack performance: corresponds to the consequent result of the attack action. This variable was evaluated using the adapted instrument of Eom and Schutz (1992) and Marcelino et al. (2011), and considered the following categories:

- Attack error: the attacker failed (the ball was played to the net, out, or fault);
- Blocked attack: the attacker was blocked by the opponent (the last one scores a point through blocking);
- Defense: the attack action did not result in a terminal action allowing, therefore, the continuity of the game by the opponent and an organized counter-attack;
- Attack point: a direct point from the attack as the ball hit the opponent's court, or the ball was deflected by the block, the defense was unsuccessful, or block error occurred.

When considering the attacks made exclusively by the middle-attacker, the direction of the attack was taken into account according to the specificity of this attacker (Costa, et al., 2016). Thus, the following categories were used:

- Hard-driven parallel attack to zone 6: attack done by players of zone 3, with a downward trajectory, directed to zone 6, by imprinting a powerful hit on the ball;
- Hard-driven diagonal attack to zone 1: attack done by players of zone 3 with a downward trajectory directed to zone 1 by imprinting a powerful hit on the ball;
- Hard-driven diagonal attack to zone 5: attack done by players of zone 3 with a downward trajectory directed to zone 5 by imprinting a powerful hit on the ball;
- Placed attack: attack done by players of zone 3 using the fingers to direct the ball to an unguarded space.

The attacks exploring the block (i.e., the ones that contact the block) were included in the previously mentioned categories according to their power and direction.

Setting type: corresponds to the type of setting specifically performed to the middle-attacker. The distance between the setter and the middle attacker and their positions (near to or far from and in front or behind the setter, respectively) were taken into account since these characteristics interfere with the type of setting. The following categories were considered:

- Right tempo (positive): the attack is performed in front or near the setter; the ball is played to the right side of the attacker's body central axis;
- Left tempo (negative): the attack is performed in front or near the setter; the ball is played to the left side of the attacker's body central axis;

- Back tempo: the attack is performed behind and near the setter;
- Seven: the attack is performed in front and away from the setter.

The middle attack offensive actions performed behind and away from the setter were not considered as a category since they did not occur in the observed matches. All the variables are organized in Table 1.

Data collection

All matches were recorded from the top of the court; the camera was positioned seven to nine meters behind the end line of the court and nearly three meters above the ground level (the distance and position were tested in the pilot study). This position cannot be changed because it is a championship rule. A Sony camera with 1080p HD resolution and 60 Hz of frequency was used for this purpose. The images were analyzed through Data Volley Software, a reliable system used in tactical training of middle blockers (Neculai, 2020).

Five observers were previously trained in order to achieve consistency in the criteria and quality of coding the data. They had a minimum of five years of experience as volleyball scouts and possessed a degree in Physical Education. Moreover, the five observers were high-level volleyball coaches and they were employed to conduct performance analyses through videos. All the observers analyzed 25% of the sample and repeated the same analysis ten days later. The lowest interclass correlation between the observers was 90%.

Statistical procedures

Descriptive statistics were applied in order to determine the frequencies and percentages of the attack performance according to the attackers' functional specialization. For the prediction data analysis, multinomial regression was used to analyze the relation of the independent variables with the dependent variables one by one. The variables showing correlation were used to make the adjusted model that verified the predictive power and influence of each of the independent variables on the dependent variable. Thus, a predictive model of the attack performed by the middle-attacker was elaborated. The independent variables were the quality of reception as well as type and direction of the attack, whereas attack performance was the dependent variable. The gross odd ratios (OR) were calculated, i.e., possibilities of an event to occur when analyzing the dependent variable with the independent variable one by one, that is, without considering the regression model. The adjusted odd ratios (ORA) were also calculated, i.e., possibilities for the event to occur when analyzing the dependent variable with the independent one within

Table 1. Variables analyzed during middle-attacker's actions

Direction	Effects of reception	Attack tempo	Attack performance	Attack direction	Setting type
Hard-driven parallel attack with the palm of the hand to zone 6	Poor quality reception (C): only wing attackers are available	First tempo of attack: take-off during or slightly after the setting	Attack error: attack played to the net, out or fault	Hard-driven parallel attack to zone 6: powerful attack from zone 3, with a downward trajectory to zone 6	Right tempo (positive): the attack is performed closer to the setter, and the ball is set on the right side of the attacker
Hard-driven diagonal attack with the palm of the hand to zone 1 and zone 5	Moderate quality reception (B): inhibit quick attacks	Second tempo of attack: take two or three steps after the setting	Blocked attack: attack blocked with the opponent's point	Hard-driven diagonal attack to zone 1: powerful attack from zone 3, with a downward trajectory to zone 1	Left tempo (negative): the attack is performed close to the setter, and the ball is set on the left side of the attacker
Placed attack, using the fingers	Excellent quality reception (A): all the attackers are available	Third tempo of attack: three steps approach after the ball reaches the peak of its ascending trajectory	Defense: attack with the opponent dig and organized counter-attack	Hard-driven diagonal attack to zone 5: powerful attack from zone 3, with a downward trajectory to zone 5	Back tempo: the attack is performed behind and closer to the setter
			Attack point: attack touches the opponent's court, block or defense without continuity, or block error	Placed attack: attack done by players of zone 3 using the fingers to direct the ball to an unguarded space	Seven: the attack is performed in front and from 1 to 2 m away from the setter

the model, that is, considering the influence of all the independent variables on the dependent variable. Thus, the predictor variables were analyzed simultaneously, so that the effect of each variable was adjusted for the effect of the others. In the treatment of the data, the significance value of 5% ($p \leq .05$) was adopted, and the SPSS software (Statistical Package for the Social Sciences) version 20.0 for Windows was used.

Reliability

For assessing reliability, 20% of the actions were re-analyzed, surpassing the reference value of 10% (Tabachnick & Fidell, 2013). The Cohen's Kappa values for inter-observer and intra-observer reliability, respectively, were: effects of reception = 0.98 and 0.96; setting type = 0.90 and 0.92; attack tempo= 0.94 and 0.96; attack type = 1.00 and 1.00; attack efficacy = 1.00 and 1.00. Hence, all these values fulfilled the criterion of 0.75 as suggested in literature (Fleiss, 2003).

Results

Table 2 presents the descriptive data regarding the effect of the attack according to the attackers' functional specialization. Significant differences were observed in the efficacy of the attack in relation to the player's functional specialization (χ^2 (2) = 353.74; p <.00001). Thus, the effectiveness of the attack performed by the middle-attacker (3.40 ± 0.93) was higher than the attack performed by the wing attacker (3.12 ± 1.01) or opposite attacker (3.08 ± 1.08).

Table 3 presents the predictive factors of the effect of the setting type when considering the middle-attacker exclusively. The results showed that the dependent variable was predicted by the independent variable (χ^2 = 297.775, p <.0001), and the right tempo increased the odds of the hard-driven diagonal attack to zone 5, the hard-driven diagonal attack to zone 1, and the hard-driven parallel attack to zone 6 (OR: 1.684; OR: 1.481; OR: 1.392, respectively). The left tempo increased the odds of the hard-driven diagonal attack to zone 5 and the hard-driven diagonal attack to zone 1 (OR: 3.308; OR: 4.202, respectively). In addition, the back tempo increased the chances of the hard-driven parallel attack to zone 6 (OR: 1.420).

Table 2. Descriptive analysis of the effect of the middle-attacker

Middle-attacker			Player's functional specialization Middle-attacker
Attack performance	Point scored	Occurred	3453
		% Attack efficacy	32.60%
		% By opposition	65.66%
	Defense	Occurred	842
		% Attack efficacy	22.54%
		% By opposition	16.01%
	Blocked attack	Occurred	597
		% Attack efficacy	18.49%
		% By opposition	11.35%
	Attack error	Occurred	367
		% Attack efficacy	19.34%
		% By opposition	6.98%
Total		Occurred	5259

Table 3. Predictive factors of the effect of the setting type performed to the middle-attacker

Setting type[a]		Odds ratio (OR)	I.C. 95%		*p*
			Inferior limit	Inferior limit	
Right tempo	Hard-driven diagonal attack to zone 5	1.684	1.278	2.219	.0001*
	Hard-driven diagonal attack to zone 1	1.481	1.103	1.988	.009*
	Hard-driven parallel attack to zone 6	1.392	1.052	1.842	.020*
	Placed attack[b]				
Left tempo	Hard-driven diagonal attack to zone 5	3.308	2.450	4.467	.0001*
	Hard-driven diagonal attack to zone 1	4.202	3.079	5.734	.0001*
	Hard-driven parallel attack to zone 6	1.305	.953	1.788	.097
	Placed attack[b]				
Back tempo	Hard-driven diagonal attack to zone 5	1.122	.835	1.508	.444
	Hard-driven diagonal attack to zone 1	1.306	.957	1.782	.092
	Hard-driven parallel attack to zone 6	1.420	1.060	1.902	.019*
	Placed attack[b]				

a. Reference category: Seven.
b. This parameter is set to zero because it is redundant.
* Difference to p<.05.

Table 4. Predictive factors of the effect of the attack performed by the middle-attacker

	Attack performance[a]	Odds ratio (OR)	Odds ratio adjusted (ORA)	I.C. 95%	
				Inferior limit	Upper limit
Attack point	Reception A	2.028	2.049	1.642	2.557
	Reception B[b]				
	Right tempo	1.766	1.751	1.309	2.343
	Left tempo	2.920	2.927	2.138	4.007
	Back tempo	1.315	1.296	.947	1.774
	Seven[b]				
	Hard-driven diagonal attack to zone 5	4.072	3.618	2.433	5.381
	Hard-driven diagonal attack to zone 1	2.873	2.444	1.632	3.658
	Hard-driven parallel attack to zone 6	3.447	3.536	2.359	5.299
	Placed attack[b]				
Defense	Reception A	.970	.981	.763	1.263
	Reception B[b]				
	Right tempo	.721	.730	.524	1.017
	Left tempo	1.069	1.161	.817	1.649
	Back tempo	1.156	1.196	.849	1.684
	Seven[b]				
	Hard-driven diagonal attack to zone 5	.429	.423	.285	.628
	Hard-driven diagonal attack to zone 1	.398	.383	.256	.573
	Hard-driven parallel attack to zone 6	.389	.383	.255	.576
	Placed attack[b]				
Blocked attack	Reception A	1.134	1.121	.861	1.461
	Reception B[b]				
	Right tempo	.952	.947	.666	1.347
	Left tempo	1.291	1.278	.880	1.856
	Back tempo	1.210	1.211	.838	1.750
	Seven[b]				
	Hard-driven diagonal attack to zone 5	1.327	1.297	.823	2.043
	Hard-driven diagonal attack to zone 1	1.163	1.115	.701	1.773
	Hard-driven parallel attack to zone 6	1.166	1.157	.726	1.845
	Placed attack[b]				

[a] Reference category: Attack error.
[b] This parameter is set to zero because it is redundant.
* Difference at p<.05

Table 4 presents the predictive factors of the attack performance when considering only the middle-attacker. The results showed that the dependent variable was predicted by the independent variables (χ^2 = 639.05, p <.0001), and the excellent quality reception, right tempo, left tempo, the hard-driven diagonal attack to zone 5 (ORA: 2.049, ORA: 2.927, ORA: 3.618, ORA: 2.444, ORA: 3.536, respectively) increased the odds of scoring a point. Additionally, the hard-driven diagonal attack to zone 5, the hard-driven diagonal attack to zone 1, and the hard-driven parallel attack to zone 6 reduced the odds of defense (ORA: 423; ORA: 383; ORA: 383, respectively).

Discussion and conclusions

This study aimed to analyze the predictive factors of attack efficacy in high-level male volleyball, taking into account the effects of reception, attack tempo, attack performance, setting type, and attack type. Globally, the results revealed that the attack point is more likely to occur after high-quality receptions (reception A), first attack tempos and hard-driven attacks. Moreover, faster attacks and hard-driven attacks decrease the chances of the opponents' defense and high-quality receptions. Previous studies also indicate that one of the predictive factors of attack efficacy is a high-quality reception, which promotes a better attack organization (Costa, et al., 2018). Accordingly, high-quality receptions afford the setter excellent setting conditions to organize a more complex attack and faster attack tempos with all attackers (Bergeles & Nikolaidou, 2011; Peiró, et al., 2016). Consequently, attack actions become more unpredictable and the opposite defensive organization less effective, which increases the possibility of points scoring (Costa, et al., 2011; Klaricic, et al., 2018). In this context, the middle attacker can be considered the most important player to attack actions' unpredictability.

When considering specifically the most effective attack of the middle players, they showed high attack efficacy. This result is consistent with previous studies that highlighted the determinant role of the middle attacker in quick attacks and, therefore, in increasing the odds of scoring a point (Costa, et al., 2016; Marcelino, Afonso, Moraes, & Mesquita, 2014). Thus, middle attackers have been considered of strategic relevance since their actions are used to provide their setters with quicker and better attack options (Afonso & Mesquita, 2011).

Concerning the predictive factors of attack performance, the results showed that the efficacy of the middle attackers was predicted by excellent quality receptions, right and left tempos and the hard-driven diagonal attack to zone 5. Moreover, powerful attacks (diagonal and parallel alike) are associated with reduced odds of defense success. As several studies have shown, the quality of the reception predicts the performance of the attack (Costa, et al., 2018; Peña, et al., 2013). Considering that the middle attacker usually attacks quick sets and, therefore, tends to attack more often when the set was made in an excellent setting zone, it could be said that there is a theoretical need for a high reception quality for the setter to set balls to the middle attacker (Costa, et al., 2016; Peiró, et al., 2016).

The novelty of this study refers to a higher chance of winning an attack point after the right (positive) and left tempo (negative) setting type. This relation may be explained by the fact that the game held near the setter improves speed and accuracy, mainly when using the positive and negative setting type, which increases the uncertainty in the opponents' block and restricts the opponents' defensive system (Peiró, et al., 2016). More specifically, during the fast middle attack, the middle blocker has to choose between jumping to block the middle attacker or trying to block the wing or opposite attacker; and the defender has less time to see the set ball (i.e., since it is really fast) and moves trying to arrive at the best position for defense. Following this reasoning, the decrement in block and defense efficacy is a consequence of the fast middle attack. Thus, the vicinity of the middle-hitter to the setter allows the latter to control the block better and, therefore, to make better decisions regarding offensive organization (Peiró, et al., 2016).

Another novelty of this study is related to the effect of the setting type performed by the middle attacker. Here, results showed that the right and left tempo increased the odds of the hard-driven diagonal attack to zone 5 and zone 1, while the back tempo increased the chances of the occurrence of the hard-driven parallel attack to zone 6. These results are in line with the study by Costa et al. (2016), when the left and right tempo settings were efficient strategies to score points in high-level men's volleyball. The use of powerful attacks by the middle attacker with these specific directions could be explained by the quality of the opponents' block. Here, the use of diagonal directions to zone 5 and zone 1 when facing a left or a right tempo could be explained as a decision to avoid a well-formed and rigid block structure presented by the opposite team. On the other hand, the decision to use a powerful parallel attack to zone 6 with a back tempo setting type could indicate that the block was broken (i.e., not well-formed) at the moment of attack. Thus, right, left and back tempo setting types seem to be used as game variations from situational demands changing the attack strategy to increase the blocking uncertainty.

Therefore, the ability of the middle attacker together with other potential factors such as technical proficiency of the players (both attackers and blockers), the height the block reaches, or even the psychological features, may be more relevant for attack efficacy than the quality of block opposition (Afonso & Mesquita, 2011; Mesquita & Graça, 2002; Queiroga, Matias, Greco, Graça, & Mesquita, 2005). This idea may be due to the nature of volleyball, which is a game of non-invasion, where the blocker cannot directly interfere with the attacker; hence, the latter always has the advantage.

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MONITORING EXTERNAL LOAD DURING REAL COMPETITION IN MALE HANDBALL PLAYERS THROUGH BIG DATA ANALYTICS: DIFFERENCES BY PLAYING POSITIONS

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Abstract:

The present study aimed to analyze the external load put on elite male handball players during the 2020 European Championship differentiated by playing positions. A system based on three phases was designed: 1) information capture of game events through sensor networks, LPS system and WebScraping techniques; 2) information processing based on Big Data Analytics; 3) extraction of results based on a descriptive analytics approach. Results showed that wings (Ws) and center backs (CBs) performed more accelerations and decelerations than the players in other positions in the entire match and attack. In defense, wings showed higher values than the rest of the players, followed by line players (LPs). In regard to body contacts, the positions that received more average number during the whole match were the CBs and LPs, with the CBs presenting the highest values in offense and the LPs in defense. Finally, backs were the ones performing more total jumps per game and in offense. In defense, LPs and left backs presented the highest values. It is necessary to monitor individual high intensity events to develop individual training programmes for different playing positions. High-intensity decelerations should be specially considered since they enlarge injury risks.

Keywords: *accelerations, decelerations, body contacts, jumps, performance analysis*

Introduction

Workload quantification is defined as the process of recording training and competition workload demands to regulate training volumes and intensities in athletes and to decrease the risk of injuries and overtraining (Bourdon, et al., 2017). Handball is a team sport that requires intermittent high-intensity actions such as accelerations, decelerations, body contacts, high-speed displacements, and jumps (Karcher & Buchheit, 2014). To be accurate, these demands should be assessed individually as each player will respond differently to the same training and competition workloads (Gómez-Carmona, Bastida-Castillo, Ibáñez, & Pino-Ortega, 2020).

The possibility of knowing and being able to monitor these high-intensity actions in real matches is the key to optimizing the training process (Font, et al., 2022), improving player's performance (Font, et al., 2021), and reducing injuries (Harper, Carling, & Kiely, 2019; Luig, et al., 2018). Coaches can now individualize players' workloads according to game demands (Barbero, Granda-Vera, Calleja-González, & Del Coso, 2014), since playing positions largely influence game demands (Manchado, Pueo, Chirosa-Rios, & Tortosa-Martínez, 2021) and may be related to metabolic power parameters (Venzke, Schäfer, Niederer, Manchado, & Platen, 2023). Furthermore, coaches could use this specific information to prepare players for the worst-case scenario, which is the highest possible demand within brief time intervals (Carton-Llorente, Lozano, Iglesias, Jorquera, & Manchado, 2023).

The way of approaching the study of external load in competition has been changing in parallel with technological advances. From the use of the video camera with manual digitization (Alexander & Boreskie, 1989) to portable microtechnology of local positioning (LPS) (Font, et al., 2021; González-Haro, et al., 2020), going through automatic tracking systems by video cameras (Manchado, Tortosa-Martínez, Vila, Ferragut, & Platen, 2013).

With the recent appearance of Sensor Networks and LPS technological development, applicable to indoor sports, a quality leap has been made in load control in indoor sports (Gómez-Carmona, et al., 2020; Kniubaite, Skarbalius, Clemente & Conte, 2019). Due to its small size and easy placement, it has allowed for studying new variables, such as jumps, shots, accelerations, etc., giving useful information and allowing to generate new analysis indexes for researchers and coaches (González-Haro, et al., 2020).

Despite the importance and growth in the number of researches and technological improvements cited, scientific knowledge about handball competition's demands is still insufficient. Previous studies have provided very limited specific information based on game-simulated situations in elite women (Luteberget & Spencer, 2017; Wik, Luteberget, & Spencer, 2017), training sessions in young players (Ortega-Becerra, Belloso-Vergara, & Pareja-Blanco, 2020), an amateur team (González-Haro, et al., 2020), or one single elite team during a season (Font, et al., 2021; Kniubaite, et al., 2019).

Thus, this study aimed to analyze position-specific physical demands elite handball players should meet in offense and defense by measuring external load during European Championship matches. These profiles can provide a benchmark for coaches to optimize individual player preparation based on the activities they perform during a major championship. To make this study feasible, it has been necessary to capture a huge amount of data from heterogeneous sources, process them to obtain value-added information and analyze them to draw conclusions that provide knowledge and can help in decision making. To this end, a specific methodology has been proposed based on sensor network technologies and Local Positioning System (LPS), Big Data Analytics, and a descriptive analytics approach.

Materials and methods

In this study, a descriptive observational cross-sectional study was used to examine external load according to playing positions and phases of the game during competitive matches. Playing phases (offense/defense) were distinguished based on ball possession and overall player movement. Ball possession was determined in an automated process in which the sensor of the ball and the sensors of the player had to move in the direction of the opponent's goal. To be considered as an offensive phase the ball must go forward in a stable possession for at least three meters and the respective team must keep the ball possession for two seconds (Venzke, et al., 2023).

Data were obtained from all the players participating in the European Handball Federation (EHF) Men's EURO 2020. This study is part of a larger study analyzing different aspects of competition physical demands in elite handball, with several studies published previously (Manchado, et al., 2021; Pueo, Tortosa-Martínez, Chirosa-Rios, & Manchado, 2022; Pueo, Tortosa-Martínez, Chirosa-Rios, & Manchado, 2023). None of these previous studies focused on high intensity activities such as accelerations, decelerations, body contacts and jumps.

In order to analyze the external load of the players, an integral system based on Sensors Network, LPS (Kinexon Precision Technologies, Munich, Germany) and Big Data Analytics (Bai & Bai, 2021; Gil, Johnsson, Mora, & Szymański, 2019) was designed. Each device, a sensor (player tag) whose dimensions were 49x33x8 millimeters (height/width/depth) and weighed 14 grams, was fitted to the back of each player with an adjustable vest. LPS Kinexon units can measure the fundamental handball movement demands in terms of peak speed, peak acceleration, and peak deceleration (Fleureau, Lacome, Buchheit, Couturier, & Rabita, 2020).

For this study, 485,806,812 records were analyzed regarding accelerations, decelerations, body contacts and jumps. Kinexon system has been validated against well-known systems such as GPS, showing proper between-device reliability (coefficient of variation around 5%) (Blauberger, Marzilger, & Lames, 2021; Fleureau, et al., 2020; Hoppe, Baumgart, Polglaze, & Freiwald, 2018).

Subjects

Data were obtained from 357 male players from 24 national teams in 65 matches, participating in the European Handball Federation (EHF) Men's EURO 2020, held in Austria/Norway/Sweden. The players were distributed in the following playing positions: left wing (LW), left back (LB), center back (CB), right back (RB), right wing (RW) and line players (LP). The goalkeepers were excluded from the study because their workload demands and technical-tactical actions differ from those of court players (Wagner, Finkenzeller, Würth, & Von Duvillard, 2014). Anthropometric characteristics and the age of the players are presented in Table 1. This information was collected from the official statistical data provided by the EHF.

The study was approved by the EHF. The players were informed of the purposes, procedures, and risks of the study and provided informed consent before the beginning of the study in a contract with the EHF. Personal data were anonymized for this study. All the procedures were conducted in accordance with the Declaration of Helsinki (World Medical Association, 2013) and approved by the Ethics Committee of the University of Alicante (registration number UA-2020-09-10).

Table 1. Physical characteristics of the players (mean ± standard deviation)

Playing position	N	Height (cm)	Body mass (kg)	BMI (kg/m²)	Age (years)
Left wing	48	186.9±5.7	84.4±7.9	24.2	28.3±4.6
Left back	73	196.1±4.2	97.2±6.5	25.3	26.8±4.7
Centre back	55	189.7±5.8	90.3±6.9	25.1	27.5±5.0
Right back	52	194.4±5.8	95.7±8.9	25.3	27.9±4.8
Right wing	50	184.6±5.4	83.1±6.3	24.4	28.0±4.4
Line player	79	196.8±4.6	105.3±8.5	27.2	28.5±4.7
Total	357	192.2±6.9	94.1±10.9	25.4	27.8±4.7

Note. BMI=body mass index.

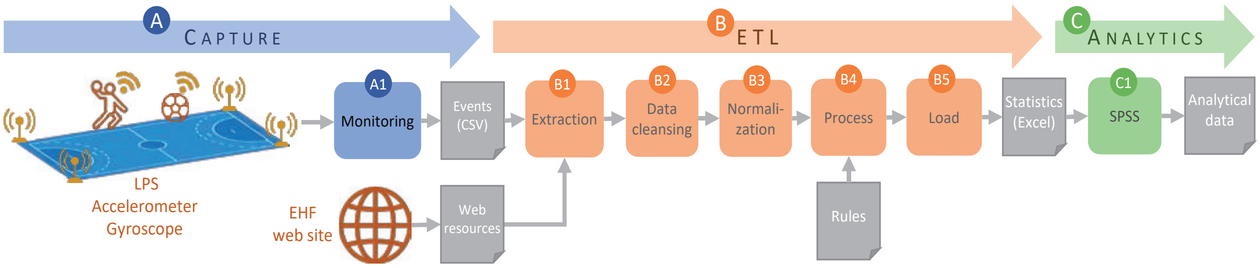


Figure 1. Modular system for data capturing, processing, and analysis.

Procedures

To carry out this study and guarantee its viability, an integral system based on Sensors Network, LPS and Big Data Analytics (Bai & Bai, 2021; Gil, et al., 2019) was designed, oriented to the characteristics and needs of handball. A large amount of information to be processed and the heterogeneity of data sources and formats made it necessary to propose a system that automated this process to obtain the information in a limited time and with adequate quality. As a result, a modular system that allowed the implementation of the proposed methodology with the objective of capturing, storing, processing, and analyzing the information necessary for this study was created (Figure 1).

The acquisition module (Figure 1 – A) was responsible for automatic acquisition of the data required for the study. On the one hand, the data was provided by the company Kinexon, through a Sensors Network system that recorded variables related to the events taking place during the matches. A LPS system, to determine the real-time position and motion data, was used to collect the positional data of players and the ball (Blauberger, et al., 2021; Luteberget & Spencer, 2017). A complete description of the system can be found elsewhere (Manchado, et al., 2020, 2021). In both cases, the sensor calculates 3D data (x, y, z) with position accuracy <10 centimeters at a sampling frequency of 20 hertz for players and 50 hertz for the ball. Additionally, the devices are capable of measuring accelerometry and orientation in all three axes.

From these data, a set of specific handball high intensity events (HIE) were identified (Figure 1 – A1): player accelerations (over 2 m/s^2), decelerations (under -2 m/s^2), body contacts (over 3G), and jumps. These HIE were divided into different categories for posterior analysis (Table 2). For the study, these data were obtained under the batch processing model and extracted from a semi-structured format based on a CSV format.

In the extract, transform and load (ETL) phase, the integration and calculation of the value-added data were carried out (Figure 1 – B). First, the multi-sources data were obtained and parsed by developing specific connectors (Figure 1 – B1). Subsequently, the data cleansing process (Figure 1 – B2) was carried out, where wrong or unnecessary records were eliminated, and incorrect, non-existent or inconsistent data were corrected or completed.

In a subsequent process, normalization and transformation of the data were carried out (Figure 1 – B3). Additionally, some variables were calculated on the fly from other records (e.g., duration and timestamps by the phases of the match). Next, the process of aggregation and integration was carried out (Figure 1 – B4). The calculation of the statistical data was parameterized using a set of declarative rules and considering offensive and defensive events. The following variables and categories (Table 2) were considered (total and per minute).

Finally, in the loading process (Figure 1 – B5), all the information was transformed into Excel format files, compatible with the Statistical Package for Social Sciences (SPSS V22.0 for Windows, SPSS Inc, Chicago, USA) software to perform statistical analysis.

Table 2. Variables and categories considered in the study

	HIA (m/s²)	HID (m/s²)	HIBD (G)	HIJ (cm)
Category 1	2-3	-2-3	3-5	<20
Category 2	3-4	-3-4	5-8	20-40
Category 3	>4	>-4	>8	>40

Note. HIA=high intensity accelerations; HID=high intensity decelerations; HII=high intensity body contacts; HIJ=high intensity jumps.

Statistical analyses

Descriptive analysis was presented as means and standard deviations. Data were analyzed for normality using the Kolmogorov-Smirnov test and for homogeneity of variances with the Levene test.

The differences between the different playing positions in regards to the average and the maximum number of accelerations, decelerations, body contacts, and jumps per game were determined by one-way analysis of variance (ANOVA) with the Brown-Forsythe correction, followed by the Games-Howell *post-hoc* testing, appropriate when there is a lack of homogeneity of variances. The effect size of the ANOVA was calculated with omega squared (ω^2), where <0.06 was a small effect, >0.06<0.14 was a medium effect, and >0.14 was a large effect (Field, 2013).

To determine the magnitude of the paired relationships resulting from the *post-hoc*, Cohen's effect size (ES) was used with a modified classification (trivial <0.2, small 0.21–0.6, moderate 0.61–1.2, large 1.21–1.99, and very large >2.0) proposed for sports sciences (Hopkins, 2002) and used in other similar handball studies (Cardinale, Whiteley, Ahmed, & Popovic, 2017; Manchado, et al., 2020). The alpha level of significance was set at $p<.05$.

Results

Table 3 shows the mean number of the total and maximum accelerations, decelerations, body contacts, and jumps per game according to the different playing positions. These values are

Table 3. Mean, standard deviation, and statistical differences in external load variables (total and maximal values) according to specific playing positions

	LW (2)	LB (3)	CB (4)	RB (5)	RW (6)	LP (7)	F(p)	ES
AccT	56.03±28.10^{3457}	34.85±18.43^{4}	43.90±20.98^{57}	36.75±16.96	51.50±29.91^{3457}	33.90±17.85	42.38 (<.001)	0.12
AccTMax	4.38±0.38^{3457}	3.85±0.49	3.95±0.41^{7}	3.85±0.38	4.39±0.38^{3457}	3.77±0.42	110.53 (<.001)	0.24
AccOff	35.38±18.64^{357}	23.34±15.76^{7}	35.54±18.54^{357}	27.14±14.02^{7}	32.20±18.82^{357}	18.19±11.35	51.72 (<.001)	0.14
AccOffMax	4.18±0.49^{3457}	3.64±0.67^{7}	3.87±0.46^{7}	3.75±0.48^{7}	4.11±0.38^{3457}	3.45±0.68	74.39 (<.001)	0.17
AccDef	21.21±10.89^{3457}	12.61±8.93	9.50±6.63	10.44±6.89	20.56±11.52^{3457}	17.53±11.82^{345}	64.30 (<.001)	0.17
AccDefMax	4.15±0.57^{3457}	3.35±0.63	3.21±0.71	3.24±0.62	4.22±0.63^{3457}	3.44±0.64^{45}	117.45 (<.001)	0.27
DecT	34.46±17.98^{357}	28.36±15.60	38.87±19.44^{357}	29.55±15.02^{7}	32.01±20.08^{7}	26.00±13.79	20.17 (<.001)	0.06
DecTMax	-4.10±0.53^{357}	-3.69±0.57	-3.98±0.55^{57}	-3.78±0.53^{7}	-4.11±0.66^{357}	-3.55±0.49	47.15 (<.001)	0.13
DecOff	20.78±12.57^{7}	18.55±11.43^{7}	28.72±15.313^{23567}	19.91±10.59	19.68±13.25	14.41±8.33	41.73 (<.001)	0.12
DecOffMax	-3.97±0.56^{357}	3.56±0.61^{7}	-3.86±0.55^{357}	-3.65±0.53^{7}	-3.95±0.71^{357}	-3.36±0.54	48.13 (<.001)	0.13
DecDef	14.01±7.29^{3457}	10.21±6.48	10.40±5.69	9.88±6.22	12.88±8.20^{345}	11.76±6.52^{35}	13.69 (<.001)	0.04
DecDefMax	-3.68±0.65^{3457}	-3.23±0.62	-3.47±0.65^{37}	-3.31±0.67	-3.70±0.69^{3457}	-3.30±0.55	25.36 (<.001)	0.07
BodycontactT	9.86±8.09	15.73±10.02^{26}	20.14±11.99^{2356}	16.52±9.27	7.59±5.32	18.07±10.72^{236}	60.85 (<.001)	0.15
BodycontactTMax	9.01±3.21	9.94±3.05^{6}	10.81±3.97^{6}	10.10±3.50^{6}	8.16±3.14	9.73±3.28	3.76 (.002)	0.05
BodycontactOff	4.23±4.30	8.37±6.66^{26}	15.53±10.03^{23567}	10.80±6.93^{2367}	3.90±3.49	8.98±7.30^{26}	92.99 (<.001)	0.21
BodycontactOffMax	8.04±3.12	9.08±3.30	10.38±4.04^{26}	9.49±3.71^{6}	7.37±3.09	8.59±3.31	4.88 (<.001)	0.06
BodycontactDef	5.63±5.31^{6}	7.35±6.88^{2456}	4.60±5.16	5.72±4.79^{6}	3.69±3.04	9.08±7.10^{23456}	36.00 (<.001)	0.09
BodycontactDefMax	7.22±3.03	7.48±2.93	6.64±2.89	7.74±2.77	7.11±2.77	7.84±2.84	1.37 (.34)	0.02
JumpT	6.68±4.89	10.85±7.32^{267}	11.36±7.74^{267}	12.09±7.65^{267}	5.75±3.98	7.17±4.79	46.11 (<.001)	0.13
JumpTMax	0.48±0.11	0.62±0.10^{267}	0.63±0.11^{267}	0.63±0.11^{267}	0.53±0.12^{7}	0.42±0.13	34.01 (<.001)	0.34
JumpOff	4.62±3.37^{7}	8.37±5.70^{267}	9.61±6.83^{267}	10.43±6.77^{2367}	4.85±3.26^{7}	3.21±2.43	84.23 (<.001)	0.23
JumpOffMax	0.46±0.12	0.61±0.11	0.62±0.11	0.64±0.12	0.50±0.13	0.38±0.14	37.12 (<.001)	0.37
JumpDef	2.89±2.41^{6}	4.32±4.50^{2456}	2.98±3.07^{6}	2.70±1.97^{6}	1.99±1.22	5.30±3.77^{2456}	28.16 (<.001)	0.11
JumpDefMax	0.40±0.11	0.41±0.12	0.37±0.15	0.37±0.11	0.38±0.13	0.39±0.12	0.69 (.625)	0.001

Note. AccT=total accelerations; AccTMax=maximum total acceleration; AccOff=Accelerations in offense; AccOffMax=maximm acceleration in offense; AccDef=accelerations in defense; AccDefMax=maximum acceleration in defense; DecT=total decelerations; DecTMax=maximum total deceleration; DecOff=decelerations in offense; DecOffMax=maximum deceleration in offense; DecDef=decelerations in defense; DecDefMax=maximum deceleration in defense; ImpctT=total body contacts; ImpctTMax=maximum total body contact; ImpctOff=body contacts in offense; ImpctOffMax=Maximum body contacts in offense; ImpctDef=body contacts in defense; ImpctDefMax=maximum body contacts in defense; JumpT=total jumps; JumpTMax=maximum total jump; JumpOff=jumps in offense; JumpOffMax=maximum jump in offense; JumpDef=jumps in defense; JumpDefMax=maximum jump in defense.

Table 4. Mean, standard deviation, and statistical differences in external load variables normalized per playing time according to specific playing positions

	LW 2	LB 3	CB 4	RB 5	RW 6	LP 7	F(p)	ES
Acc (min)	1.68±0.45^{7}	1.45±2.92	1.61±0.58^{7}	1.81±3.99	1.71±1.66^{7}	1.19±0.36	3.31(.006)	0.01
AccOff	1.07±0.32^{7}	1.04±2.84^{7}	1.33±0.60^{2367}	1.38±3.25^{2367}	1.09±0.90^{7}	0.69±0.40	12.20(<.001)	0.03
AccDef	0.63±0.22^{347}	0.45±0.30^{4}	0.32±0.18	0.47±0.90	0.66±0.80^{347}	0.56±0.27^{34}	12.32(<.001)	0.04
Dec (min)	1.05±0.32^{7}	1.14±0.68	1.41±0.56^{267}	1.36±2.25^{7}	1.05±0.84	0.92±0.32	6.80(<.001)	0.02
DecOff	0.63±0.24^{7}	0.77±1.42^{7}	1.05±0.44^{2367}	0.96±1.81^{67}	0.64±0.42^{7}	0.51±0.24	12.20(<.001)	0.03
DecDef	0.43±0.17	0.38±0.32	0.37±0.20	0.41±0.48	0.42±0.47	0.41±0.16	1.20(.30)	0.004
Bodycontact (min)	0.30±0.21	0.62±0.66^{26}	0.71±0.32^{267}	0.74±1.37^{26}	0.26±0.37	0.63±0.30^{26}	21.20(<.001)	0.06
BodycontactOff	0.13±0.12	0.35±0.60^{26}	0.55±0.28^{2367}	0.49±1.00^{2367}	0.13±0.17	0.33±0.25^{26}	26.28(<.001)	0.07
BodycontactDef	0.17±0.16	0.27±0.32^{246}	0.16±0.17	0.25±0.47^{6}	0.13±0.23	0.30±0.20^{246}	15.59(<.001)	0.04
Jumps (min)	0.20±0.13	0.41±0.45^{267}	0.39±0.21^{267}	0.54±1.29^{267}	0.21±0.48	0.23±0.13	12.27(<.001)	0.04
JumpsOff	0.14±0.09^{7}	0.34±0.47^{267}	0.34±0.20^{267}	0.47±1.14^{267}	0.17±0.43	0.11±0.08	16.37(<.001)	0.05
JumpsDef	0.08±0.07	0.14±0.11^{246}	0.09±0.08	0.10±0.19	0.07±0.09	0.17±0.11^{2456}	19.08(<.001)	0.08

Note. Acc=total accelerations per minute; AccOff=accelerations in offense per minute; AccDef=accelerations in defense per minute; Dec (min)= total decelerations per minute; DecOff=decelerations in offense per minute; DecDef=decelerations in defense per minute; Impcts=total body contacts per minute; ImpctOff=body contacts in offense per minute; ImpctDef=body contacts in defense per minute; Jumps=total jumps per minute; JumpOff=jumps in offense per minute; JumpDef=jumps in defense per minute.

presented for the total game, as well as segmented by offense and defense. Table 4 shows the mean number of these same events according to the minutes played by each player. Both tables also present the results of the one-way ANOVA, showing the statistical differences between the different playing positions, and the effect size of the ANOVA. The effect sizes of the paired differences are represented in Figure 2. In supplementary files, the mean values for the different categories established for each high-intensity event analyzed can be found.

Accelerations

Wings showed the highest total number of accelerations per game showing moderate effect sizes (*d*=0.8–1.0) when compared to RBs, LBs and LPs, and a small effect size with CBs (LW, *d*=0.5; RW=0.2), who presented the second highest values considering the entire game. In the offensive phase, CBs and wings were the positions with more activity, while in the defensive phase, LPs were the ones showing the second highest values after the wings. The highest differences were found between the LWs and the CBs in defense (55% lower; *d*=1.3), and between the LWs and the LPs in offense (48% lower; *d*=1.2). Similar results were found when analyzing separately the three categories of accelerations established but with higher effect sizes found in the differences between the wings and the rest of the players in category 2 (entire game, *d*=1.0-1.5; offense, *d*=0.7-1.5; defense, *d*=0.7-1.6) and category 3 (entire game, *d*=1.3-1.6; offense, *d*=0.8-1.3; defense, *d*=1.3-1.4).

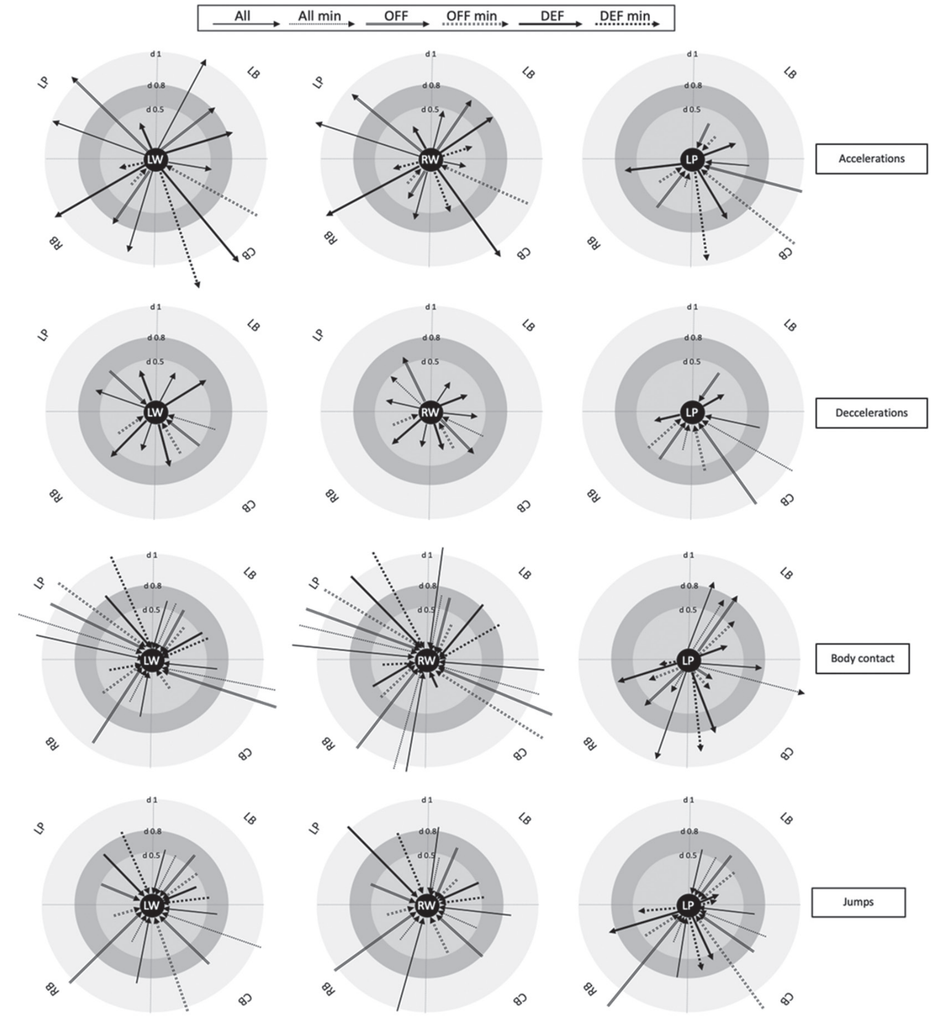
When data were normalized per minutes played, wings showed similar total values to the rest of the players for the entire game other than LPs, who presented the lowest values (30% lower than wings). In offense, CBs and RBs were the ones presenting higher values, while wings showed the highest values in defense. However, when analyzing these differences by categories, wings showed again the highest number of accelerations compared to the rest of the players for categories 2 and 3, showing in this last category the highest effect sizes (entire game, *d*=0.8-1.6; offense, *d*=0.4-1.1; defense, *d*=1.1-1.3).

The average maximum acceleration was also found for the wings, with medium to large size effects for the entire game (*d*=1.0-1.5) and the defensive phase (*d*=1.1-1.5), and medium for the offensive one (*d*=0.6-1.1).

Decelerations

In regard to decelerations, CBs showed the highest number of total decelerations (20-26% higher than the other backs and the LPs, *d*=0.3-0.7) and decelerations in the offensive phase (28-30% higher than wings and the other backs, *d*=0.5-0.7; 50% higher than LPs, *d*=1.2). In defense, wings presented the highest values (23-25% higher than backs, *d*=0.5-0.6). However, if we analyze the data segmented by categories, in categories 2 and 3 wings showed higher values than any other playing position with the highest effect sizes found in category 3 (entire game, *d*=0.3-0.9; offense, *d*=0.3-1.0; defense, *d*=0.3-0.4).

When analyzing normalized values, CBs and RBs were the ones presenting the higher total (20-35% higher, *d*=0.3-1.1) and offensive values (30-50% higher, *d*=0.2-1.5), while in defense no significant differences were found for any playing position. When analyzing by categories, wings



Note. Acc All=total accelerations; Acc All min=total accelerations per minute; AccOFF=accelerations in offense; AccOFF min=accelerations in offense per minute; AccDEF=accelerations in defense; AccDEF min=accelerations in defense per minute; Dec All=total decelerations; Dec All min=total decelerations per minute; Dec OFF=decelerations in offense; Dec OFF min=decelerations in offense per minute; Dec DEF=decelerations in defense; Dec DEF min=decelerations in defense per minute; BC All=total body contacts; BC All min=total body contacts per minute; BC OFF=body contacts in offense; BC OFF min=body contacts in offense per minute; BC DEF=body contacts in defense; BC DEF min=body contacts in defense per minute; Jum All=total jumps; Jum All min=total jumps per minute; Jum OFF=jumps in offense; Jum OFF min=jumps in offense per minute; Jum DEF=jumps in defense; Jum DEF min=jumps in defense per minute.

Figure 2. Effect sizes of the paired differences in the number of high intensity events per game between the different playing positions.

presented the highest values in category 3 for the entire game compared to LBs, CBs, and LPs (*d*=0.3-0.8) as well as for offense but only significant when compared to LPs (*d*=0.7). In defense, RWs showed the highest values compared to all the other playing positions including LWs (*d*=0.3-0.5).

Wings and CBs presented the highest values of average maximum decelerations for the entire game and offense (13-15% higher than LPs, *d*=0.9-1.0; 6-10% higher than LBs and RBs, *d*=0.5-0.7), while wings showed the highest values in defense (5% higher than CBs, *d*=0.3; 10-13% higher than LBs, RBs, and LPs, *d*=0.5-0.7).

Body contacts

CBs and LPs showed the highest number of body contacts in the entire game (55% higher than wings, *d*=0.8-1.3; 20% higher than RBs and LBs, *d*=0.2-0.3), with CBs showing the highest values in offense (73% higher than wings, *d*=1.4-1.5; 40% higher than LBs, RBs and LP, *d*=0.5-0.8), and LPs in defense (55% higher than RWs, *d*=0.9; 45% RBs, *d*=0.5; 35% LWs and RBs, *d*=0.2-0.5; 22% LBs; *d*=0.2). In category 3, LBs, RBs, and CBs showed the highest number of body contacts (55% higher than RWs, *d*=0.3-0.5).

According to time played, CBs and RBs received a higher average number of body contacts than wings (57%, *d*=0.4-1.4) in the entire game. Wings also presented the lowest values for offense with significant differences with the rest of the playing positions (80% less than RBs and CBs, *d*=0.5-1.8; 66% lower than LBs and LPs, *d*=0.4-1.0), and in defense with the LBs, RBs and LPs (60% lower, *d*=0.2-0.7). In category 3, there were no differences between the playing positions.

In regard to maximum body contacts, CBs and RBs showed higher values than the RWs in the entire game (*d*=0.7 and *d*=0.5, respectively) and offense (*d*=0.8 and *d*=0.6, respectively), while no significant differences were found in defense.

Jumps

LBs, RBs, and CBs were the players performing more total jumps per game (45% more than wings, *d*=0.6-1.0; 35% more than LPs, *d*=0.6-0.8) and in offense (44% more than wings, *d*=0.7-1.0; 66% more than LPs, *d*=1.2-1.5). In defense, LPs and LBs presented the highest values (50-60% higher than the rest, *d*=0.4-1.0). LBs and CBs showed the highest number of jumps in category 3 for the entire game and offense (LWs, RWs, and LPs, *d*=1.0-1.2; RBs, *d*=0.3-0.5). In defense, LPs were the ones presenting a higher number of jumps in this category (LWs, RWs, CBs, RBs, *d*=0.3-0.4).

Considering normalized data, LBs, RBs, and CBs still showed the highest average number of jumps per game and in offense (37-45%, *d*=0.3-1.5). In defense, LPs and LBs showed the highest values (+28-58%, *d*=0.2-0.9). These differences remained significant when analyzing separately category 2 (entire game, *d*=0.5-1.4; offense, *d*=0.5-1.7; defense, *d*=0.3-0.8) and category 3 (entire game, *d*=0.5-1.3; offense, *d*=0.5-1.4) but with higher effect sizes, except in defense where LPs only show significantly higher values than LW (*d*=0.2) and RW (*d*=0.3).

In regard to maximum jumps, LBs, RBs, and CBs also showed the highest values in the entire game (*d*=0.7-1.6) and offense (*d*=1.0-1.8), while no significant differences were found for defense.

Discussion and conclusions

The main goal of this study was to define and compare high intensity events' (HIE) demands of professional handball at the top-level championship by playing positions and the phase of the game. The HIE analyzed were players' accelerations, decelerations, body contacts, and jumps. To the best of our knowledge, this is the first time that the HIE performed by all players in all games through the entire EURO have been analyzed using an integrated system based on Sensors Network, LPS, and Big Data Analytics.

Accelerations and decelerations

Players' ability to accelerate and decelerate is particularly important in meeting tactical and technical demands in handball. Our results indicate that all players performed more high intensity accelerations (HIA) (over 2 m/s^2) than high intensity decelerations (HID) (under -2 m/s^2). This is in line with García et al. (2022) who found greater number of accelerations and covered distance during these actions than decelerations. This is also valid for different team sports like basketball, futsal, rink hockey or soccer. Harper et al. (2019) found that in all team sports apart, from American football, there seemed to be a greater frequency of high-intensity decelerations compared to accelerations. In contrast, Font et al. (2021) did not find differences in the number of accelerations and decelerations. In any case, handball induces one of the highest deceleration loads for players in team sports (Harper, et al., 2019). Therefore, we agree with Font et al. (2021) regarding the importance of monitoring decelerations due to their great involvement in the possibility of injury and overload of the player. Coaches should know and comprehensively monitor all the HIAs and HIDs as separate load indexes, as has been done in this study, and try to relate the data to the incidence of injuries in their teams.

In the present study, the wings and CBs performed more HIA and HID than the other positions on average in a match. In the highest intensity category (category 3), the wings were the ones that accelerated and decelerated the most at an absolute level. These data are in line with those obtained in other studies (Manchado, et al., 2013) but differ from those of Font et al. (2021), a study where CBs were the most active players, and González-Haro et al. (2020) and Luteberget et al. (2017) where the backs showed higher values for amateur men and elite women players, respectively.

In offense, wings and CBs again showed the highest number of HIA and HID, while LPs showed the lowest values. In defense, wings were the ones showing higher values than the rest of the players, followed by LPs. This fact perfectly reflects the game, the CBs and wings being the more dynamic players in offense and the LPs, having to play between the defenders, the more static ones. CBs are the organizers of the offensive game, and thus changes of pace are fundamental to overcome the defense, while wings, due to the space limitation of this position, need to show high acceleration and deceleration values to succeed. In defense, LPs are changed very often and when they defend, they usually show more activity in the center of the defense.

If we normalize the data according to the time spent on the court, the differences disappear for HIA in the whole match, due to less playing time for backs and LPs (Manchado, et al., 2021), a position that showed 30% fewer accelerations than the wings. These results are in line with those of Font et al. (2021). The normalized results for HIDs showed significant differences between the CBs and the wings (+25%) or the LPs (+35%) getting closer to those from Font et al. (2021) and Gonzalez de Haro et al. (2020). In offense, the RBs and CBs showed the highest load of HIA and HID compared to the other positions (almost 50% more than the LPs and approx. 30% more than all other playing positions). Greater involvement of these positions in tactical play could explain these higher values per minute played. In defense, results do not differ much from the absolute values.

Similarly to other studies (González-Haro, et al., 2020; Manchado et al., 2013), the maximum accelerations and decelerations presented by the wings in offense and defense were greater than in therest of the specific positions (around 20% difference), again possibly due to the space limitation of this position.

Body contacts

Concerning the body contacts, there are again clear differences between the playing positions. In this case, CBs and LPs are the positions that receive more high intensity body contacts (HIBC) during the whole match and the wings the least. Back players receive the highest number of hard body contacts. These results are partially in line with those of Gonzalez de Haro et al. (2020) who also showed the CBs and LPs as the positions with more HIBD, although in our study the differences with the wings are greater, probably because we also included the defense phase data.

In the offensive phase, the CBs received significantly more body contacts than the rest of the players and wings the least. The CB is the one that plays the most in proximity to the defense and with the greatest defensive pressure since the CB is the main builder of the offense. This trend of greater participation of the CB is even clearer when analyzing by categories of global intensity (50% of the average in category 2 and 40% in category 3).

In defense, the LPs are the ones that executed the most body contacts and again the wings the least. This could be due to the position the LPs normally occupy in central areas of defensive systems. For the same reason, the LBs also showed more body contacts than the rest of the players (15% more than the average). These differences, with some nuances, were maintained when analyzed more deeply by high-intensity categories (categories 2 and 3). When normalizing by time played, there were no longer differences between the LBs and RBs, the positions that also have a very important role in defense.

Jumps

The backs showed significantly more jumps per game and in offense. This behavior is clearer in intensity categories 2 and 3 where the differences in some cases increase above 75%. These results are in line with Povoas et al. (2014) showing backcourt players 60% higher values than wings (19.1±5.2 vs 8.2±2.9). The total number of jumps in our study is higher (8.6) compared to amateur players' studies. Chelly et al. (2011), Gonzalez de Haro et al. (2020), and Povoas et al. (2012) found values of 6.9, 4.3 and 4.9 jumps per player during the match, respectively. Probably, the high demands of the EURO are responsible for the differences. Back players are not only jumping more but they are also the ones performing the highest jumps in the entire game and offense. Due to the tactical needs of the game to overcome defensive barriers, the number and intensity of jumps made by the backs are higher. In defense, the LBs and LPs showed more jumps and the wings, especially the RWs, the least. The LPs were the ones presenting a higher number of jumps in category 3, probably because they usually occupied central defensive positions thus having to jump when trying to block shots taken by the opposing backcourt players.

Limitations

One of the limitations we have found is that the comparison between studies is complicated. The number of investigations with a similar aim is very limited and those that have been carried out are analyzing different populations with different instruments. Another limitation is that the tactical playing systems and playing styles used have not been taken into consideration, which would undoubtedly have influenced the load differentiation as they play a crucial role in performance (Abdelkrim, Castagna, El Fazaa, & El Ati, 2010). It would be interesting to know, for example, how the use of a 5:1 defense influences HIE as opposed to a 6:0. Furthermore, although the Kinexon system has been validated previously, body contacts and jumps as well as the different categories established have not been validated specifically.

Practical applications

The results of the present study represent possible reference values for male elite handball players. In this sense, wings presented the highest absolute values of HIA and HID. Coaches should consider bringing to specific tournaments like the European Championship an extra wing player or a polyvalent player, distribute better the minutes played over the competition in this position avoiding excessive fatigue and possible injuries. Backs and LPs should train with lower volumes but at higher intensities. Traditionally, CBs have been included in the group of backs, but actually, their external load is more similar to that of the wings. Therefore, it would be appropriate to establish at least three working groups: CBs and wings, backs, and LPs. Finally, the differences found between the players regarding offense and defense should also be considered, establishing different training programmes accordingly.

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Declaration of interest

The authors report there are no competing interests to declare.

Supplemental Digital Content: Mean, standard deviation and statistical differences from the ANOVA in the three subcategories of each high intensity event normalized by time played

	LW 2	LB 3	CB 4	RB 5	RW 6	LP 7
AccT/min	1.69±0.25^{7}	1.45±2.93	1.62±0.59^{7}	1.82±4.00	1.71±1.67^{7}	1.20±0.36^{246}
Cat 1	0.91±0.30	1.10±2.23	1.20±0.40^{267}	1.36±2.88	0.87±0.68	0.87±0.31
Cat 2	0.63±0.25^{3457}	0.31±0.58^{6}	0.38±0.24^{67}	0.42±1.09^{6}	0.70±0.91^{3457}	0.30±0.21^{246}
Cat 3	0.15±0.12^{3457}	0.04±0.15	0.04±0.06^{7}	0.04±0.17	0.15±0.21^{3457}	0.02±0.04
AccOff/min	1.07±0.33^{47}	1.04±2.84	1.33±0.61 ^{267}	1.38±3.26^{7}	1.09±0.91^{7}	0.69±0.40^{2456}
Cat 1	0.55±0.22^{7}	0.75±2.10	0.96±0.41^{267}	0.99±2.27^{267}	0.54±0.42	0.48±0.29
Cat 2	0.43±0.20^{347}	0.24±0.58^{6}	0.34±0.24^{67}	0.34±0.95^{6}	0.48±0.54^{7}	0.18±0.21
Cat 3	0.08±0.09^{3457}	0.03±0.15	0.03±0.06^{7}	0.03±0.17	0.08±0.16 ^{357}	0.01±0.04
AccDef/min	0.63±0.25^{347}	0.46±0.31^{47}	0.32±0.19^{67}	0.48±0.91	0.66±0.80	0.57±0.28
Cat 1	0.36±0.17^{4}	0.36±0.28^{4}	0.24±0.17	0.38±0.73	0.34±0.29^{4}	0.42±0.23^{34}
Cat 2	0.20±0.11^{3457}	0.08±0.09^{467}	0.05±0.06^{67}	0.08±0.21^{67}	0.23±0.41^{7}	0.12±0.11
Cat 3	0.07±0.07^{3457}	0.01±0.02	0.01±0.02	0.01±0.03	0.08±0.14^{3457}	0.01±0.02
DecT/min	1.06±0.33^{47}	1.15±1.69^{47}	1.42±0.56^{67}	1.37±2.25^{7}	1.05±0.85	0.92±0.33
Cat 1	0.77±0.25	0.92±1.13	1.08±0.43^{267}	1.08±1.69^{67}	0.74±0.72	0.75±0.26
Cat 2	0.24±0.14^{47}	0.21±0.44^{4}	0.29±0.20^{7}	0.26±0.59	0.25±0.19^{7}	0.16±0.16
Cat 3	0.04±0.06^{57}	0.02±0.14^{6}	0.03±0.05^{567}	0.02±0.05^{6}	0.06±0.08^{7}	0.01±0.04
DecOff/min	0.63±0.25^{47}	0.78±1.42^{7}	1.05±0.44^{67}	0.96±1.82^{7}	0.65±0.43^{7}	0.52±0.25
Cat 1	0.44±0.19	0.61±1.00	0.81±0.37^{2367}	0.74±1.26^{267}	0.43±0.35	0.41±0.19
Cat 2	0.16±0.11^{47}	0.14±0.30^{4}	0.21±0.15^{67}	0.21±0.58^{7}	0.17±0.14^{7}	0.09±0.11
Cat 3	0.03±0.05^{57}	0.02±0.14	0.02±0.04^{57}	0.01±0.04	0.04±0.07^{457}	0.01±0.02
DecDef/min	0.44±0.17^{4}	0.39±0.32	0.37±0.20	0.42±0.49	0.43±0.47	0.41±0.16
Cat 1	0.34±0.15^{4}	0.31±0.21	0.28±0.15	0.35±0.47	0.32±0.41	0.34±0.15^{4}
Cat 2	0.08±0.07	0.06±0.16	0.08±0.09	0.05±0.07^{246}	0.08±0.09	0.07±0.08
Cat 3	0.01±0.02	0.01±0.02	0.01±0.03	0.01±0.02	0.02±0.04^{2357}	0.01±0.03
ImpactsT/min	1.31±0.95^{3457}	2.69±2.41^{467}	2.50±0.94^{67}	2.85±5.02^{67}	1.13±1.36^{7}	3.89±1.40
Cat 1	0.23±0.18	0.49±0.50^{26}	0.56±0.27^{26}	0.56±0.93^{26}	0.19±0.24	0.53±0.26^{26}
Cat 2	0.04±0.06^{3457}	0.10±0.18^{46}	0.13±0.10^{67}	0.14±0.34^{6}	0.04±0.14^{7}	0.08±0.08
Cat 3	0.01±0.04	0.02±0.07	0.02±0.04	0.03±0.16	0.01±0.02^{346}	0.01±0.03
ImpactsOff/min	0.50±0.30^{3457}	1.09±1.89^{467}	1.65±0.73^{67}	1.40±2.12^{67}	0.50±0.78^{7}	2.06±1.43
Cat 1	0.09±0.10	0.27±0.45^{26}	0.42±0.22^{2367}	0.35±0.54^{26}	0.09±0.12	0.27±0.22^{26}
Cat 2	0.02±0.04^{3457}	0.07±0.16^{46}	0.11±0.09^{67}	0.11±0.34^{67}	0.02±0.07^{7}	0.05±0.06
Cat 3	0.01±0.03^{4}	0.02±0.04	0.02±0.03^{7}	0.02±0.16	0.00±0.01^{347}	0.01±0.02
ImpactsDef/min	0.85±0.85^{357}	1.65±1.33^{46}	0.90±0.81^{67}	1.49±3.15^{6}	0.68±0.66^{7}	1.90±1.12
Cat 1	0.14±0.14	0.23±0.28^{246}	0.14±0.15	0.22±0.47^{6}	0.10±0.16	0.26±0.18^{246}
Cat 2	0.02±0.03^{3}	0.03±0.07	0.02±0.04	0.03±0.04	0.02±0.08	0.04±0.05^{245}
Cat 3	0.00±0.02	0.01±0.05	0.00±0.01	0.01±0.02	0.00±0.01	0.01±0.02
Jumps/min	0.21±0.13^{345}	0.42±0.45^{67}	0.40±0.22^{67}	0.54±1.29^{67}	0.21±0.49	0.24±0.14
Cat 1	0.13±0.09	0.14±0.29	0.13±0.11	0.15±0.48	0.13±0.39	0.15±0.10
Cat 2	0.05±0.07^{345}	0.14±0.17^{67}	0.15±0.11^{7}	0.18±0.33^{67}	0.03±0.04^{7}	0.06±0.07
Cat 3	0.02±0.03^{3457}	0.12±0.12^{567}	0.10±0.10^{567}	0.20±0.49^{67}	0.02±0.07^{7}	0.01±0.03
JumpsOff/min	0.15±0.10^{3457}	0.34±0.47^{67}	0.34±0.20^{67}	0.48±1.15^{67}	0.18±0.43	0.11±0.09
Cat 1	0.10±0.08^{7}	0.08±0.29	0.10±0.10^{7}	0.11±0.33	0.10±0.33	0.07±0.07
Cat 2	0.02±0.04^{3457}	0.10±0.16^{67}	0.13±0.10^{67}	0.16±0.33^{67}	0.03±0.04^{7}	0.01±0.03
Cat 3	0.01±0.03^{3457}	0.11±0.11^{67}	0.09±0.09^{567}	0.19±0.49^{67}	0.02±0.07^{7}	0.00±0.02
JumpsDef/min	0.09±0.07^{37}	0.15±0.12^{46}	0.09±0.08^{7}	0.11±0.20^{7}	0.08±0.10^{7}	0.17±0.11
Cat 1	0.03±0.05	0.06±0.08^{246}	0.03±0.05	0.05±0.17	0.03±0.08	0.08±0.082^{23456}
Cat 2	0.02±0.04^{367}	0.04±0.06^{456}	0.02±0.04^{67}	0.02±0.04^{67}	0.01±0.02^{7}	0.05±0.06
Cat 3	0.00±0.01	0.01±0.02^{6}	0.01±0.02	0.01±0.03	0.00±0.01	0.01±0.02^{26}

AccT/min=total accelerations per minute; AccOff/min=Accelerations in offense per minute; AccDef/min=Accelerations in defense per minute; DecT/min= total decelerations per minute; DecOff/min=decelerations in offense per minute; DecDef/min=decelerations in defense per minute; ImpactsT/min=total impacts per minute; ImpactOff/min=impacts in offense per minute; ImpactDef/min=impacts in defense per minute; JumpsT/min=total jumps per minute; JumpOff/min=jumps in offense per minute; JumpDef/min=Jumps in defense per minute; Cat 1=category 1; Cat 2=category 2; Cat 3=Category 3; p>.05 for superscripts numbers.

Supplemental Digital Content: Mean, standard deviation and statistical differences from the ANOVA in the three subcategories of each high intensity event normalized by time played

TOTAL	LW 2	LB 3	CB 4	RB 5	RW 6	LP 7
Acc	56.04±28.10^{3457}	34.85±18.44	43.90±20.98^{357}	36.75±16.97	51.51±29.91^{457}	33.90±17.86
Cat 1	30.43±16.41^{37}	26.44±14.09^{3567}	32.78±15.47	28.57±14.20^{7}	27.17±16.65	25.23±14.16
Cat 2	21.05±12.20^{3457}	7.53±5.72^{4}	10.26±6.58^{57}	7.64±4.54	20.41±12.84^{3457}	8.10±5.59
Cat 3	4.57±3.95^{3457}	0.66±1.04	0.86±1.28^{567}	0.55±0.94	3.93±3.65^{3457}	0.48±0.95
AccOff	35.39±18.65^{357}	23.34±15.76^{7}	35.55±18.55^{357}	27.15±14.03^{7}	32.21±18.83^{37}	18.20±11.36
Cat 1	18.31±10.47^{7}	16.81±11.71^{7}	25.97±13.37^{23567}	20.35±11.33^{367}	16.85±10.74^{7}	12.87±8.82
Cat 2	14.43±9.03^{3457}	5.41±4.96^{4}	8.73±6.10^{57}	6.05±4.26^{7}	13.74±9.09 ^{3457}	4.43±4.11^{456}
Cat 3	2.49±2.70^{34567}	0.47±0.92^{7}	0.70±1.23^{57}	0.41±0.77	1.64±2.17^{3457}	0.25±0.68^{23456}
AccDef	21.22±10.90^{3457}	12.62±8.93^{457}	9.50±6.64^{7}	10.44±6.89^{7}	20.57±11.52^{3457}	17.53±11.83
Cat 1	12.23±7.38^{345}	9.88±7.08^{4}	7.07±5.53	8.42±5.82	10.82±6.71^{4}	12.91±9.30^{3456}
Cat 2	6.67±4.19^{3457}	2.18±2.64^{4567}	1.59±1.98^{67}	1.63±1.68^{67}	6.98±4.67^{7}	3.83±3.65
Cat 3	2.10±2.06^{3457}	0.19±0.48	0.17±0.48	0.14±0.48	2.39±2.26 ^{3457}	0.24±0.68
DecT	34.46±17.98^{357}	28.37±15.61^{4}	38.87±19.44^{567}	29.56±15.02^{7}	32.02±20.09^{7}	26.01±13.79
Cat 1	25.48±13.48^{7}	23.29±12.94	29.91±15.04^{23567}	23.61±12.23	22.37±14.24	21.45±11.78
Cat 2	7.75±5.46^{357}	4.62±3.81^{46}	7.92±5.53^{57}	5.34±3.85^{67}	7.92±6.13^{7}	4.15±3.50
Cat 3	1.23±1.39^{3457}	0.37±0.80	0.89±1.11^{357}	0.48±0.85^{7}	1.59±1.83^{3457}	0.27±0.79
DecOff	20.78±12.58^{47}	18.55±11.43^{47}	28.73±15.31^{567}	19.91±10.59^{7}	19.68±13.26^{7}	14.42±8.34
Cat 1	14.68±9.26^{7}	14.80±9.37^{7}	22.17±12.00^{23567}	15.49±8.56^{67}	13.06±9.01	11.65±7.10
Cat 2	5.19±4.23^{357}	3.26±2.87^{467}	5.80±4.26^{57}	3.95±3.07^{67}	5.40±4.71^{7}	2.48±2.50
Cat 3	0.91±1.13^{357}	0.25±0.58^{467}	0.64±0.89^{567}	0.31±0.63^{67}	1.05±1.40^{7}	0.13±0.48
DecDef	14.01±7.29^{3457}	10.22±6.49^{67}	10.40±5.70^{6}	9.89±6.22^{67}	12.88±8.21	11.77±6.53
Cat 1	10.90±6.02^{345}	8.67±5.92	7.90±4.72	8.16±5.48	9.69±6.40^{4}	9.91±5.88^{45}
Cat 2	2.59±2.16^{357}	1.38±1.63	2.18±2.08^{357}	1.41±1.42	2.64±2.24^{357}	1.69±1.71
Cat 3	0.32±0.54^{3567}	0.12±0.41	0.26±0.56^{3}	0.18±0.44	0.56±0.86 ^{3457}	0.14±0.51
Impacts	9.86±8.09	15.73±10.02^{26}	20.14±11.99^{2356}	16.52±9.27	7.59±5.32	18.07±10.72^{236}
Cat 1	7.64±6.40	12.53±7.61^{27}	15.80±9.73^{2356}	12.82±7.65^{27}	5.49±4.55	15.17±9.30^{2356}
Cat 2	1.40±1.92^{3457}	2.40±2.87^{46}	3.69±3.00^{567}	2.94±2.42^{67}	1.12±1.47^{7}	2.31±2.08
Cat 3	0.36±1.33	0.56±1.54	0.58±0.80	0.50±0.88	0.21±0.48^{3457}	0.40±0.71
ImpactsOff	4.23±4.30	8.37±6.66^{26}	15.53±10.03^{23567}	10.80±6.93^{2367}	3.90±3.49	8.98±7.30^{26}
Cat 1	3.03±2.87	6.40±5.23^{26}	11.85±7.92^{23567}	8.03±5.52^{26}	2.82±2.90	7.38±6.16^{26}
Cat 2	0.74±1.29^{3457}	1.49±1.87^{456}	3.13±2.71^{567}	2.24±2.09^{67}	0.59±0.93^{7}	1.26±1.56
Cat 3	0.26±1.08	0.36±0.78	0.49±0.72^{7}	0.36±0.68	0.11±0.32^{3457}	0.25±0.57
ImpactsDef	5.63±5.31^{6}	7.35±6.88^{2456}	4.60±5.16	5.72±4.79^{6}	3.69±3.04	9.08±7.10^{23456}
Cat 1	4.65±4.67^{6}	6.27±5.38^{2456}	4.08±4.50^{6}	4.87±4.18^{6}	2.79±2.55	8.03±6.18^{23456}
Cat 2	0.66±1.08	0.93±1.71^{46}	0.58±1.03	0.72±0.99	0.56±0.96	1.09±1.29^{2456}
Cat 3	0.11±0.41	0.21±0.99	0.08±0.29	0.15±0.43	0.11±0.36	0.16±0.44
Jumps	6.68±4.89^{345}	10.86±7.33^{67}	11.36±7.75^{67}	12.09±7.65^{67}	5.76±3.98^{7}	7.18±4.80
Cat 1	4.12±2.95^{5}	3.51±3.22	3.64±3.05	3.28±2.62	3.46±2.89	4.38±3.24^{345}
Cat 2	1.53±2.25^{345}	3.76±3.34^{67}	4.40±3.62^{67}	4.25±3.42^{67}	1.12±1.47^{7}	1.83±2.17
Cat 3	0.56±1.38^{345}	3.24±3.21^{567}	2.87±2.97^{567}	4.26±3.89^{67}	0.58±0.93	0.44±1.01
JumpsOff	4.62±3.38^{3457}	8.37±5.70^{567}	9.61±6.84^{67}	10.43±6.77^{67}	4.86±3.27^{7}	3.22±2.43
Cat 1	3.01±2.34^{357}	1.66±1.87	2.79±2.44^{357}	2.21±1.87^{3}	2.79±2.54^{37}	2.02±2.01
Cat 2	0.76±1.41^{3457}	2.64±2.71^{4567}	3.68±3.26^{67}	3.62±3.16^{67}	0.82±1.21^{7}	0.32±0.69
Cat 3	0.41±1.13	3.01±3.12	2.72±2.88	4.14±3.79	0.48±0.82	0.13±0.58
JumpsDef	2.90±2.41^{367}	4.32±4.51^{456}	2.99±3.07^{67}	2.70±1.97^{67}	1.99±1.23^{7}	5.31±3.78
Cat 1	1.12±1.41^{6}	1.90±2.56^{2456}	0.88±1.44	1.10±1.52^{6}	0.69±0.98	2.47±2.41^{23456}
Cat 2	0.77±1.34	1.15±1.99^{56}	0.75±1.51	0.65±0.99^{3}	0.30±0.59^{23457}	1.57±1.99^{245}
Cat 3	0.15±0.46	0.24±0.58^{6}	0.15±0.48	0.13±0.38	0.11±0.32	0.33±0.78^{2456}

AccT=total accelerations; AccOff=Accelerations in offense; AccDef=Accelerations in defense; DecT= total decelerations; DecOff=decelerations in offense; DecDef=decelerations in defense; ImpactT=total impacts; ImpactOff=impacts in offense; ImpactDef=impacts in defense; JumpsT=total jumps; JumpsOff=jumps in offense; JumpsDef=Jumps in defense; Cat 1=category 1; Cat 2=category 2; Cat 3=Category 3; p>0.5 for superscripts numbers.

THE INFLUENCE OF SPORT-SPECIFIC FACTORS ON SLEEP QUALITY IN YOUNG ELITE ATHLETES: A COMPARATIVE STUDY

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Abstract:

Sleep is a crucial physiological process that promotes human health and well-being. Physical activity and sports participation are known to improve sleep quality in adolescents. The objective was to investigate how the characteristics of different sports affected this relationship in elite athletes. This cross-sectional study analyzed data from 1,831 young Spanish elite athletes (1,059 males and 772 females) from 11 to 20 years old who self-reported their sleep quality using the Pittsburgh Questionnaire and provided information on their sports practice. Technical sports reported significantly better sleep quality than team sports (p=.004, d =-0.39, small). Additionally, individual competition sports reported better sleep quality than team competition sports (p=.033, d=-0.15, trivial). Differences by the type of metabolism were not statistically significant. Better sleep quality was reported in outdoors training environment sports compared to indoors training environment sports (p=.023, d=-0.11, trivial). The type of sports practiced may influence sleep quality in adolescents and highlights the importance of considering sport characteristics when promoting sleep health. Further research is necessary to explore the underlying mechanisms and to validate these findings across different age groups and populations.

Keywords: *sleep quality, adolescents, elite sport, health, athletes*

Introduction

Sleep is a vital physiological process that plays a crucial role in promoting human health and well-being (Maquet, 2001). It enables the body to undergo restorative processes, repair tissues, consolidate memories, and regulate biological functions. In children, adequate sleep is essential for growth, development, cognitive function, emotional well-being, and physical health (Hirshkowitz, et al., 2015). During sleep, the body releases growth hormones that facilitate the growth and repair of tissues, muscles, and bones (Van Cauter & Plat, 1996). Sufficient sleep has been shown to improve memory, attention, and learning, which is particularly important for students (Mason, Lokhandwala, Riggins, & Spencer, 2021).

On the other hand, lack of sleep has been associated with various health issues such as obesity, diabetes, cardiovascular disease, and immune system dysfunction (Hale & Guan 2015). Thus, obtaining enough sleep quality is crucial for maintaining overall health and reducing the risk of chronic diseases later in life. The term sleep quality is prevalent in sleep medicine, yet it encompasses a multifaceted and challenging-to-objectively-measure phenomenon. It encompasses various quantitative aspects, such as total sleep time, sleep onset latency, sleep maintenance, total wake time, sleep efficiency, and, at times, sleep disruptive events like spontaneous arousal or apnea (Fabbri, et al., 2021). However, the factors influencing sleep quality may differ among individuals. Large-scale population surveys frequently rely on general inquiries regarding habitual sleep quality and the presence of sleep disturbances.

The existing body of academic literature provides compelling evidence supporting the beneficial impact of adequate sleep quality on the athletic performance and injury rates of youth athletes. Sufficient sleep duration and quality are associated with enhanced physical and cognitive abilities, leading to improved sports-related outcomes (Bonnar, Bartel, Kakoschke, & Lang, 2018). Moreover, ample sleep has been linked to reduced injury risks and faster injury recovery rates in this population (Viegas, et al., 2022). While the influence of sleep on sports in youth athletes has been extensively examined, there remains a notable gap in research regarding the reciprocal relationship: how sports engagement may affect the quality of sleep among young athletes. Investigating the bidirectional association between sports participation and sleep quality in this demographic would contribute significantly to our comprehensive understanding of the interplay between sleep and sports performance.

Parents and caregivers should prioritize creating a healthy sleep environment and establishing consistent sleep routines for children and adolescents to ensure optimal health and well-being. Emerging research has underscored the significance of adopting appropriate sleep behaviors to achieve optimal sleep quality among young individuals (Rebello, Roberts, Fenuta, Cote, & Bodner, 2022). In this context, sports engagement emerges as a compelling and intriguing factor that could potentially contribute to attaining proper sleep quality. Physical activity can assist in establishing a regular sleep schedule and promoting good sleep hygiene (Brand, et al., 2016). It can be a beneficial strategy as exercise helps regulate the body's circadian rhythm, the internal clock that controls the sleep-wake cycle (Haupt, et al., 2021). Regular physical activity has been associated with improved sleep patterns and duration in various age groups, including youth athletes (Kredlow, Capozzoli, Hearon, Calkins, & Otto, 2015). Exercise also promotes relaxation before bedtime, improves sleep quality, and reduces sleep latency (Kelley & Kelley, 2017; Reid, et al., 2010). Moreover, it has been observed to increase the duration of slow-wave sleep, which is the most restorative stage of sleep (Park, et al., 2021). Nevertheless, while there is promising evidence, additional systematic investigations are warranted to comprehensively understand the extent to which physical activity can influence sleep behaviors and quality, thus fostering a better grasp of this intriguing association.

While it is generally acknowledged that physical activity and sports positively impact sleep quality in adolescents, recent research suggests that the higher the competition level, the better the sleep quality may be due to increased physical exertion and improved sleep hygiene linked to mental focus during competition (Pano-Rodriguez, et al., 2023). Therefore, it would be valuable to analyze how the characteristics of different sports mediate this positive influence on sleep quality. Factors such as the types of movements involved, the intensity and duration of the movements, and the social dynamics of competition and workouts could potentially influence sleep quantity and quality. Investigating these factors could provide insights into optimizing the sleep benefits of sports participation for adolescents.

One factor that may influence sleep quality in sports is the nature of social interactions involved in competition (team or individual sports). Social support has consistently been shown to have a positive impact on sleep quality and it reduces sleep disturbances (van Schalkwijk, Blessinga, Willemen, Van Der Werf, & Schuengel, 2015). Team sports, which involve collaboration and social support among group members, may have an even greater beneficial effect on sleep quality compared to individual sports or disciplines. However, negative interactions and conflicts within team sports could lead to heightened stress levels and potentially impact negatively sleep quality. Additionally, individual sports may also involve collaboration and social support among athletes, albeit in different ways. Further research should be done to examine the impact of variations in social interactions within sports on sleep outcomes.

The metabolic demands specific to each sport may also be a significant factor that strongly influences sleep quality in adolescent athletes. Different sports require varying levels and types of physical exertion, which may have distinct effects on the physiological and psychological mechanisms underlying sleep. Both aerobic and anaerobic metabolism have been shown to be effective in promoting sleep (Kovacevic, Mavros, Heisz, & Fiatarone, 2018). However, more studies are required to establish strong evidence regarding which type of metabolism is more effective in promoting sleep quality.

The impact of the training environment on sleep quality has not been extensively studied in scientific literature. Yet, it is an important factor of sports that may have significant implications for children's sleep health. Differences in light exposure due to factors such as indoor versus outdoor training facilities could affect sleep quality, as light plays a crucial role in regulating circadian rhythms

(Czeisler 2013). Future research should explore the relationship between the training environment and sleep quality to better understand their potential impact on athletes' well-being and performance.

In conclusion, various factors related to the nature of sports can influence sleep quality in practitioners, particularly adolescents for whom adequate rest is crucial. Therefore, this study aims to compare the sleep quality among young elite athletes participating in various sports disciplines.

Methods

Study design

This study was designed as a cross-sectional investigation based on self-reported data and was conducted following the principles of the Declaration of Helsinki. The study protocol was reviewed and approved by the Clinical Research Ethics Committee of Aragón (PI17/0339). The presented results correspond to the baseline data collected between January and March 2018.

The study was widely disseminated by a group of volunteer independent evaluators who specialize in health sciences. Invitations were extended to all Spanish national and autonomous sports federations, high schools sports performance programs, and sports technification centers. Furthermore, 20 clubs per summer Olympic sports discipline were invited to participate, selected based on their ranking or performance level in national or international competitions among young athletes, and stratified by sex.

The study began with a concise and explicit introduction, which was followed by a thorough explanation of the various components of the questionnaires. To evaluate sleep quality, the Pittsburgh Questionnaire was utilized, as it has appropriate psychometric characteristics, including high internal consistency and test-retest reliability as well as convergent/divergent validity with sleep, psychological, and sociodemographic variables (Fabbri, et al., 2021). For individuals, information regarding their sports involvement was collected by requesting information regarding the level of competition. In addition, participants reported their height and weight to calculate their body mass index. The participants were informed about the anonymous and voluntary nature of their participation and were given an unlimited amount of time to complete the questionnaires, which took an average of 40 minutes to complete.

Participants

The current investigation conducted a survey using a representative sample of Spanish children and adolescent elite athletes aged between 11 and 20 years. All participants were selected based on general inclusion criteria. These criteria required the absence of any chronic diseases as well as the engagement in elite training and competition for a sports discipline included in the Summer Olympic Games program for at least two days per week for a minimum of six months. Additionally, participants were required to compete in the highest national category for their age in their respective sports. Among a total of 1,836 potentially eligible participants, 1,831 adolescent elite athletes (1059 males and 772 females) were included in the study sample by completing the baseline evaluation and providing valid data for sleep quality, body composition, and physical activity, as depicted in Table 1. Based on the level of competition, 193 athletes competed at the international level, and 1638 athletes competed at the national level.

Outcomes

Sleep quality (Pittsburgh Questionnaire)

The Pittsburgh Sleep Quality Index (PSQI) is a reliable and valid screening tool used to assess sleep dysfunction in both clinical and non-clinical samples (Buysse, Reynolds, Monk, Berman, & Kupfer, 1989). It has been found to have moderate

Table 1. Sample characteristics

Variable	All (N =1831)	Male (n = 1059)	Female (n = 772)
Age (year) [a]	15.51±1.98	15.64±1.94	15.33±2.03
Tanner stage, I–V [b]	50 / 143 / 569 / 853 / 201	31 / 101 / 373 / 445 / 100	19 / 42 / 196 / 408 / 101
Height (cm) [a]	169.32±11.19	173.80±10.64	163.17±8.73
Weight (kg) [a]	59.75±13.08	64.06±13.39	53.8±9.98
BMI ($kg{\cdot}m^{-2}$) [a]	20.64±3.00	21.02±3.03	20.12±2.89
Years of practice [a]	7.08±3.40	7.24±3.45	6.86±3.31
Hours per week [c]	10.00 (6.00–15.00)	10.00 (6.00–15.00)	10.00 (6.00–15.00)
Days per week [c]	5.00 (4.00–6.00)	5.00 (4.00–6.00)	5.00 (4.00–6.00)

Note. [a] Data are presented as mean (± SD), and differences between type-of-sport categories were examined by the analysis of the variance. [b] Data are presented as frequency (%), and differences between type-of-sport categories were examined by the independent-samples chi-square test. [c] Data are presented as median (IQR), and differences between type-of-sport categories were examined by the Kruskal-Wallis test.

structural validity across various populations, indicating that it is effective in fulfilling its intended purpose (Mollayeva, et al., 2016). The PSQI consists of 19 questions that cover seven components of sleep quality, including subjective sleep quality, sleep duration, sleep latency, habitual sleep efficiency, sleep disturbance, use of sleep medication, and daytime dysfunction. Each of these components is rated on a 3-point scale, with higher scores indicating poorer sleep quality. The total score, which ranges from 0 to 21, is the sum of all component scores. This tool has been validated for use in assessing the sleep quality of adolescents as well (de la Vega, et al., 2015). The PSQI is a sensitive measure that can identify individuals with poor sleep quality, comparable to more invasive clinical and laboratory measures such as polysomnography. Good sleep quality was considered when PSQI Score≤5, while poor sleep quality was considered when PSQI Score>5.

Type of sport

The adapted classification system proposed by Sundgot-Borgen and Larsen (2007) was applied to differentiate between different types of sports, including endurance, power, team, racket, combat, gymnastic, and technical sports (see Table 1 in the supplemental material).

Type of competition

The adapted guidelines for coding sports as team or individual (Zhou, Heim, &O'Brien, 2015) were applied to classify the sports in the study. Team sports were differentiated into those with opponents and those without opponents based on whether the practitioners competed simultaneously on the same competition ground. Additionally, the study identified a group of athletes who indicated that they primarily competed both individually and in a non-opponent team sport (see Table 2 in the supplemental material).

Type of metabolism

This study applied the classification system proposed by Spencer, Bishop, Dawson, Goodman, and Duffield (2006) and Spencer and Gastin (2001), which categorizes sports based on their predominant metabolism into alactic, lactic, aerobic, and mixed metabolism. This system enabled a more comprehensive analysis of the physiological demands of each sport (see Table 3 in the supplemental material).

Training environment

A differentiation was made between sports that are typically trained and competed outdoors and those that are typically done indoors (see Table 4 in the supplemental material).

Control variables

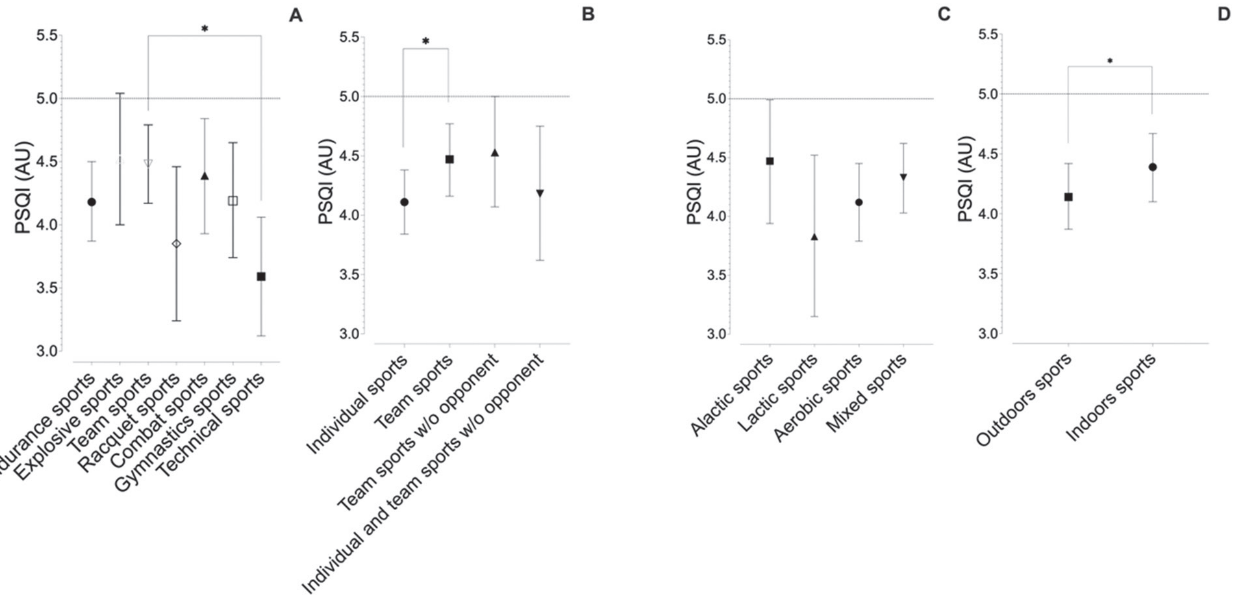
To ensure the validity of the findings, the analysis controlled for several potential confounding factors such as sex, biological age, pubertal status (Petersen, et al., 1988), province where participant lives, number of population of the participants' zone of living, socioeconomic status (Moreno-Maldonado, Ramos, Moreno, & Rivera, 2019), physical activity level (Voss, Dean, Gardner, Duncombe, & Harris, 2017), years of training, hour per week of training, and days per week of training (McMahon, et al., 2017). The control variables were selected based on their known influence on the outcomes and their potential to impact the relationship between the independent and dependent variables. By accounting for these variables, the study aimed to isolate the effect of the independent variable on the dependent variables and reduce the risk of spurious associations.

Statistical analysis

Continuous variables are presented as mean (SD), and categorical variables are presented as absolute frequency. Normality distribution of the data was checked using the Kolmogorov-Smirnov test, the Anderson-Darling test, and exploring the Q-Q plots. Homogeneity was assessed by Levene's and Bartlett's tests. Data not following normal distribution were log-transformed (Hopkins, Marshall, Batterham, & Hanin, 2009) before further analysis.

To assess the effect of type of sport (endurance, explosive sport, team sport, racquet, combat sport, gymnastics, technical), type of competition (individual, team, team without opponent, individual and team without opponent), predominant metabolism of the sport (alactic, lactic, aerobic, mixed) and training environment (outdoors, indoors) on the sleep quality scores (PSQI), an analysis of covariance (*ANCOVA*), using sex, age, pubertal status, province, population, economic status, physical activity, years of experience, hours per week of training and days per week of training, values as covariates were used. When a significant difference was found between the groups, Bonferroni *post-hoc* tests were used to determine the source. Effect sizes were calculated using Cohen's d to further quantify between-group differences and were interpreted as: <0.2= *trivial*; 0.2-0.6=*small*; 0.6-1.2=*moderate*; 1.2-2.0=*large*; >2.0=*very large* (Hopkins, et al., 2009). Adjusted marginal means with 95% CI were reported.

The level of significance was set at 0.05 for all tests. All statistical analyses were performed using JAMOVI for Mac (version 2.3.22; Sidney, Australia; retrieved from https://www.jamovi.org) (The Jamovi project, 2022). Data are presented as mean (SD), median (Mdn), and the interquartile range (IQR) Q1 (25^{th})–Q3 (75^{th}), or frequency, depending upon the type of data.



Note. Data are presented as adjusted means and 95% confidence interval. Estimated mean and 95% confidence intervals (CIs; error bars) represent values after adjusting by sex, age, pubertal status, province, population, economic status, physical activity, years of experience, hours per week of training and days per week of training of the participants. The dashed lines indicate the good/poor sleep quality threshold according to the Pittsburgh Sleep Quality Index questionnaire (PSQI). Good sleep quality: PSQI Score ≤5; poor sleep quality: PSQI Score>5. * Shows statistically significant differences between the categories (p Bonferroni ≤.05).

Figure 1. Differences in sleep quality by A) type of sport, B) type of competition, C) metabolism, and D) place of training.

Results

Sleep quality scores by the type of sport

Results for PSQI score by the type of sport are shown in Figure 1A and Table 5 (in the supplemental material). A total of 1,787 participants were included in this analysis due to different reasons detailed in Table 1 of the supplemental material. Statistically significant differences between the types of sports were reported (F=3.09, p=.005) and *post-hoc* test revealed lower PSQI scores in technical sports than in team sports (3.59 AU 95% *CI* [3.12, 4.06] vs. 4.48 AU 95% *CI* [4.17, 4.79], p=.004, d=- 0.39 95% *CI* [-0.59, -0.18], small).

Sleep quality scores by the type of competition

Results for PSQI score by the type of competition are shown in Figure 1B and Table 6 (in the supplemental material). The whole sample was included in this analysis. Statistically significant differences between the types of competition were reported (F=3.30, p=.020) and *post-hoc* test revealed lower PSQI scores in individual competition sports than in team competition sports (4.11 AU 95% *CI* [3.84, 4.38] vs. 4.47 AU 95% *CI* [4.16, 4.77], p=.032, d =- 0.15 95% *CI* [-0.26, -0.05], trivial).

Sleep quality scores by the type of metabolism

Results for PSQI score by the type of metabolism are shown in Figure 1C and Table 7 (in the supplemental material). A total of 1,644 participants were included in this analysis due to different reasons explained in Table 3 (in the supplemental material). Non-statistically significant differences between the types of metabolism were reported (F=1.55, p=.200).

Sleep quality scores by the training environment

Results for PSQI score by the training environment are shown in Figure 1D and Table 8 (in the supplemental material). The whole sample was included in this analysis. Statistically significant differences between training environments were reported (F=4.63, p=.032) and *post-hoc* test revealed lower PSQI scores in outdoors training environment sports than in indoors training environment (4.14 AU 95% *CI* [3.87, 4.42] vs. 4.39 AU 95% *CI* [4.10, 4.67], p=.032, d=- 0.11 95% *CI* [-0.20, -0.01], trivial).

Discussion and conclusions

The present study aimed to investigate the influence of different sports on sleep quality among young elite athletes, with a focus on examining the potential mediating role of the type of competition, predominant metabolism of the sport, and training environment. Specifically, we sought to explore how the nature of different sports may impact sleep outcomes in this population and to identify potential underlying mechanisms that could help explain these effects. By examining these factors, we aimed to gain a better understanding of the complex relationships between sports participation and sleep quality in adolescents and to identify potential avenues for promoting healthy sleep behaviors within this group. The results of this investigation suggest that adolescents who participate in elite sports generally exhibit good sleep quality, regardless of the specific nature of their sport. Previous analyses have even found a positive correlation between competition level and both sleep quality and regularity (Alves Facundo, et al., 2022; Pano-Rodriguez, et al., 2023).

In summary, our analysis revealed that sleep quality varies based on the type of sport, with higher sleep quality observed among individuals involved in technical sports compared to team sports. This may be attributed to the fact that technical sports, such as golf (57% of the total), horse riding, surfing, archery, and Olympic shooting, require a higher socioeconomic level, making them less accessible to the general population, especially adolescents. While we controlled for socioeconomic level statistically, it appears to be the clear reason for better sleep quality and other related factors such as nutritional aspects, etc. Another aspect that could explain these differences is that more than 90% of the subjects who compete in technical sports do their sports outdoors, which do not occur with the same percentage in other sports.

The results of this study showed that athletes participating in individual sports had better sleep quality than those in team sports, likely because technical sports are typically individual based. Different theories could explain why individual sports are associated with better sleep than team sports. One of them is that individual sports could imply higher aerobic metabolism and therefore more energy expenditure than team sports (in our database of 936 categorized individual athletes, 355 of them, or 37.9%, were also categorized as aerobic sports athletes; in contrast, none of the 668 categorized team sport athletes, or 0%, were categorized as aerobic sports athletes). This higher energy expenditure may lead to increased fatigue at bedtime, promoting better sleep quality. Furthermore, out of the 936 categorized individual athletes, 574 of them (61.3%) were also categorized as outdoor sports athletes. In contrast, only 245 out of the 668 categorized team sport athletes (36.7%) were categorized as outdoor sports athletes. These findings suggest that the main theory behind the significant differences in sleep quality between individual and team sports is associated, at least in part, with two controlled variables: type of metabolism and training environment.

Driller et al. (2022) obtained findings slightly differing from those of this study. The authors found that athletes involved in team sports exhibited lower sleep quality scores (1.1±0.6) compared to those engaged in individual sports (1.0±0.7), but they found no statistically significant difference between the groups (p=.38). Their results, different compared to ours, could be attributed to their considerably smaller sample size (N=407). Besides, it is important to consider that the average age of their sample was six years older than ours. The age difference between the two studies could potentially be a contributing factor to the variation in results, as age has been known to influence sleep patterns and behaviors among athletes.

Alves Facundo et al. (2022) found similar results to those in our study, despite using a different tool to assess the sleep. They observed better sleep parameters in individual sports in relation to sleep regularity in their cross-sectional study consisting of 172 athletes (25 ± 7 years) of different sports. Similar to our study, most of their sample were international and national athletes. Nevertheless, some new research needs to be done to deeply investigate the differences in sleep quality among young practitioners of team and individual sports and identify the factors that may influence their sleep patterns.

This study did not find any significant differences in sleep quality based on the predominant metabolism of the sports practiced. The mechanisms underlying the beneficial effects of aerobic and anaerobic exercise on sleep are not yet fully understood, but several hypotheses have been proposed. It seems that both of them could interfere with sleep by increasing levels of brain chemicals such as serotonin and endorphins (Di Liegro, Schiera, Proia, & Di Liegro, 2019), which are associated with improved mood and relaxation and may promote better sleep. Regarding aerobic exercise, it has been shown to have a cumulative effect on reducing cortisol levels, which can lead to long-term improvements in sleep quality (Beserra, et al., 2018; De Nys, et al., 2022). Concerning anaerobic exercise, it could potentially improve sleep by decreased symptoms of depression or anxiety, alterations in energy expenditure, increase in body temperature, or relief of musculoskeletal pain (Uchida, et al., 2012). Our results suggest a possible trend towards better sleep quality in sports with a higher prevalence of aerobic metabolism. This tendency is aligned with a review conducted by Vlahoyiannis et al. (2021), which found that athletes in anaerobic sports had slightly less rapid eye movement (REM) sleep compared to athletes in aerobic or mixed sports, based on sleep architecture.

Athletes training in outdoor environments showed significantly better sleep quality than those training in indoor facilities. A recent research established that low daytime light exposure is a noteworthy environmental variable that has been demonstrated to impact sleep and circadian rhythm negatively (Burns, et al., 2021). Low daytime light exposure refers to a lack of exposure to natural light during the day, particularly in the morning and early afternoon (Khalsa, Jewett, Cajochen, & Czeisler, 2003). This can occur when individuals spend most of their time indoors or in dimly lit environments, such as office buildings or indoor training facilities. Therefore, engaging in indoor physical activity could potentially affect sleep quality in a less effective way than outdoor physical activity due to the reduced exposure to natural light.

While the present study does not directly explore the implications of sleep quality on athletic performance, we believe that a comprehensive understanding of the interplay between sleep and sports performance is integral. Research findings indicate that the extension of sleep duration yielded the most advantageous outcomes for subsequent performance. Adequate sleep has been extensively linked to various physiological and cognitive processes crucial for optimal athletic functioning, including muscle recovery, energy restoration, reaction times, and overall mental acuity (Bonnar, et al., 2018). Future research endeavors could delve into investigating how variations in sleep patterns, sleep duration, and sleep disturbances might impact the training, competition outcomes, and long-term development of young athletes. By considering both perspectives, we can gain a more holistic insight into the dynamic relationship between sleep and sports, thus enabling more informed recommendations for enhancing athletic achievement and overall well-being among youth athletes.

This study has notable strengths that increase confidence in the results. Specifically, the large sample size improves the accuracy of the findings, and the recruitment of participants from across the entire country provides insight into the sleep and physical habits of the entire Spanish elite youth population. However, there are also some limitations to consider. For instance, the study did not account for other factors that might affect the results, such as training schedules, nutrition, or screen time. Additionally, some might argue that the study lacked objective measurements of activity and sleep. Nevertheless, previous research has shown that subjective reports of sleep quality are reliable, and the methods used in this study to assess sleep quality have been validated (de la Vega, et al., 2015). One last limitation of the present study could be the omission of consideration for competition schedules when assessing athletes' sleep patterns. While the study aimed to comprehensively capture athletes' sleep behaviors in their daily lives, the exclusion of competitive events—a pivotal but limited aspect of athletes' routines—neglects potential disruptions to sleep quality that are well-documented in the literature. The impact of competitions on sleep quality is established, particularly within elite athletes. Therefore, not accounting for competition-related sleep disturbances represents a limitation as it overlooks potentially unique sleep dynamics associated with these events.

To enhance the practical implications of our findings, we recognize the significance of exploring sport-specific sleep characteristics as a basis for targeted intervention strategies. Utilizing established tools like the Athlete Sleep Screening Questionnaire (ASBQ) by Samuels, James, Lawson, and Meeuwisse (2016) could offer a systematic approach to assess and manage sleep in elite athletes. By considering sport-specific sleep patterns and employing validated assessment tools, practitioners and researchers could tailor interventions to address unique sleep challenges within different sports. This approach could maximize the potential impact of our findings, providing a comprehensive framework to improve sleep quality and overall well-being among athletes.

In conclusion, adolescents who participate in elite sports generally exhibit good sleep quality, with higher sleep quality observed among individuals involved in technical and individual sports compared to team sports. However, no significant differences were found in sleep quality based on the predominant metabolism of the sports practiced. Athletes training in outdoor environments showed significantly better sleep quality than those training in indoor facilities. The findings of this study have several implications for promoting healthy and individualized sleep behaviors among young elite athletes. Firstly, coaches, parents, and healthcare professionals could consider encouraging talented adolescents with sleep disorders by increasing the opportunities for outdoor training, which may promote better sleep quality compared to indoor sports. Additionally, participating mainly in individual sports could have a positive impact on sleep.

Recognizing the relationship between modifiable sleep behaviors and sleep difficulty is crucial when considering our study's implications. Emerging evidence highlights the vital link between adaptable sleep habits and increased sleep difficulties (Mason, Stewart, Kniewasser, & Zech, 2022). This insight holds relevance for actionable insights in future research and for practitioners aiming to enhance sleep quality in athletes and the broader population. Identifying specific modifiable sleep behaviors linked to sleep difficulty informs intervention strategies and enhances the practical value of our findings. Acknowledging this dimension expands the potential impact of our study, guiding targeted interventions and evidence-based recommendations to promote improved sleep hygiene and overall well-being of the youth.

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SUPPLEMENTAL MATERIAL

Type of sport

Table 1. Classification of sports according to type of sport

Endurance sports (n = 512)	Calm water canoeing, cycling, long distance athletics running, middle-distance athletics running, race athletics walking, rowing, swimming, triathlon.
Explosive sports (n = 105)	Athletics combined events, athletics jumping events, athletics sprints (< 15 sec), athletics throwing events, weightlifting.
Team sports (n = 666)	Baseball, basketball, beach volleyball, field hockey, football, handball, rugby, volleyball, water polo.
Racquet sports (n = 65)	Badminton, table tennis, tennis.
Combat sports (n = 143)	Boxing, fencing, judo, karate, taekwondo, wrestling.
Gymnastic sports (n = 167)	Artistic gymnastics, artistic swimming, rhythmic gymnastics, trampoline gymnastics.
Technical sports (n = 129)	Archery, equestrian, golf, shooting, surfing.

Note. Out of the initial sample of participants, 44 subjects were excluded from the analysis for various reasons. 15 subjects who were competing in sailing and 13 subjects who were competing in whitewater canoeing were excluded because their sports could not be clearly categorized. Additionally, 12 subjects who were competing in athletics and 4 subjects who were competing in climbing were excluded because they primarily competed in sports that could fit into multiple categories depending on the specific type of sport.

Type of competition

Table 2. Classification of sports according to type of competition

Individual sports (n = 936)	Archery, artistic gymnastics, athletics, badminton, boxing, canoeing, climbing, cycling, equestrian, fencing, golf, judo, karate, rhythmic gymnastics, rowing, shooting, surfing, swimming, table tennis, taekwondo, tennis, trampoline gymnastics, triathlon, weightlifting, wrestling.
Team sports with opponents (n = 668)	Baseball, basketball, beach volleyball, field hockey, football, handball, rugby, volleyball, water polo.
Team sports without opponents (n = 142)	Flatwater canoeing, rhythmic gymnastics, rowing, sailing, synchronized swimming.
Individual and team sports without opponents (n = 85)	Flatwater canoeing, rhythmic gymnastics, rowing, synchronized swimming.

Type of metabolism

Table 3. Classification of sports according to their predominant metabolism

Alactic sports (n = 104)	Athletics combined events, athletics jumping events, athletics speed events (< 15 sec), athletics throwing events, weightlifting.
Lactic sports (n = 51)	Athletics speed events (15-60 sec), BMX cycling, calm water canoeing (15-60 sec), swimming speed events (15-60 sec).
Aerobic sports (n = 448)	Athletics long-distance events, athletics middle-distance events (> 60 sec), calm water canoeing (> 60 sec), mountain biking, race athletics walking, road cycling, rowing, swimming long-distance events, track cycling, triathlon.
Mixed sports (n = 1041)	Artistic gymnastics, badminton, baseball, basketball, beach volleyball, boxing, fencing, field hockey, handball, judo, karate, rhythmic gymnastics, rugby, soccer, synchronized swimming, taekwondo, tennis, trampoline gymnastics, volleyball, water polo, whitewater canoeing, wrestling.

Note. A total of 187 subjects were excluded from the analysis for various reasons, including: 15 subjects competing in archery, 15 subjects competing in equestrian, 73 subjects competing in golf, 15 subjects competing in sailing, 14 subjects competing in surfing, 12 subjects competing in shooting and 13 subjects competing in table tennis were excluded because their sports were deemed to have no direct relationship with metabolism as a determinant of sports performance. In addition, 16 subjects who competed in athletics and 10 subjects who competed in swimming were excluded because they primarily competed in sports modalities that could fit into multiple categories depending on the specific type of metabolism.

Training environment

Table 4. Classification of sports according to the training environment

Outdoors (n = 935)	Archery, athletics, baseball, BMX cycling, canoeing, equestrian, field hockey, football, golf, mountain biking, road cycling, rowing, rugby, sailing, surfing, tennis, triathlon.
Indoors (n = 896)	Artistic gymnastics, artistic swimming, badminton, basketball, boxing, fencing, handball, judo, karate, rhythmic gymnastics, shooting, swimming, table tennis, taekwondo, track cycling, trampoline gymnastics, volleyball, water polo, weightlifting, wrestling.

Table 5. Differences in sleep quality between the types of sport

Variable	Endurance sports (n = 512)	Explosive sports (n = 105)	Team sports (n = 666)	Racquet sports (n = 65)	Combat sports (n = 143)	Gymnastics sports (n = 167)	Technical sports (n = 129)
PSQUI (AU)	4.18 (3.87, 4.50)	4.52 (4.00, 5.04)	4.48 (4.17, 4.79)	4.18 (3.87, 4.50)	4.39 (3.93, 4.84)	4.19 (3.74, 4.65)	3.59 (3.12, 4.06) *S

Note. Data are presented as adjusted marginal mean (95% CI). * Shows statistically significant differences from the team sport category ($p \leq .05$). S small effect size. AU: arbitrary units.

Table 6. Differences in sleep quality between the types of competition

Variable	Individual sports (n = 936)	Team sports with opponents (n = 668)	Team sports without opponent (n = 142)	Individual and team sports without opponents (n = 85)
PSQUI (AU)	4.11 (3.84, 4.38) *T	4.47 (4.16, 4.77)	4.53 (4.07, 5.009)	4.18 (3.62, 4.75)

Note. Data are presented as adjusted marginal mean (95% CI). * Shows statistically significant differences from the team category ($p \leq .05$). T trivial effect size. AU: arbitrary units.

Table 7. Differences in sleep quality between the predominant metabolisms.

Variable	Alactic sports (n = 104)	Lactic sports (n = 51)	Aerobic sports (n = 448)	Mixed sports (n = 1041)
PSQUI (AU)	4.47 (3.94, 4.99)	3.83 (3.15, 4.52)	4.12 (3.79, 4.45)	4.33 (4.03, 4.62)

Note. Data are presented as adjusted marginal mean (95% CI). AU: arbitrary units.

Table 8. Differences in sleep quality between places of training

Variable	Outdoors sports (n = 935)	Indoors sports (n = 896)
PSQUI (AU)	4.14 (3.87, 4.42) *T	4.39 (4.10, 4.67)

Note. Data are presented as adjusted marginal mean (95% *CI*). * Shows statistically significant differences from the indoors category ($p \leq .05$). T trivial effect size. AU: arbitrary units.

COMPARISON OF EXTERNAL LOAD DURING PRE-MATCH WARM-UP AMONG DIFFERENT AGE CATEGORIES FROM THE SAME FOOTBALL PROFESSIONAL CLUB

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Abstract:

The aim of the present study was to compare the external load (EL) of the football pre-match warm-up (WU) in absolute terms and as a percentage (%) of the individual match demands. A total of 96 football players from different age categories participated in the study: professional (PRO, n=26), reserve (RES, n=22), under-21 (U21, n=28) and U18 (n=20) teams. Eleven EL variables were obtained through global positioning system devices. The results show that there are differences among teams in total duration, total distance, number of accelerations and decelerations, acceleration load, distance covered at different speed ranges and the maximum velocity, both expressed absolutely and relative to the match demands. The EL of the WU represents a variable percentage depending on a particular variable with respect to the match, ranging from ≈5% for high-speed running or very high-speed running to ≈20% for acceleration-load. The conclusions were: 1) the WU load represents an important part of the EL on players in soccer matches, and 2) the PRO team presented a lower EL in most of the variables, being consistent in both absolute and relative terms to the match demand. The strength and conditioning coaches must be cautious not to cause fatigue in the players while guaranteeing an adequate set-up to dispute the match.

Keywords: *GPS, soccer, team sport, elite, training load, age-group*

Introduction

The warm-up (WU) is a protocol specifically undertaken to prepare athletes for the onset of subsequent physical tasks (McCrary, Ackermann, & Halaki, 2015) that can be a training session or a competition. It aims at increasing neural activation and raising core and skeletal muscle temperature (Zois, Bishop, & Aughey, 2015) in order to increase blood flow and optimize metabolic responses during exercise (e.g., faster oxygen uptake kinetics) (Maturana, Peyrard, Temesi, Millet, & Murias, 2018). Several researches have shown that a well-structured active warm-up can increase performance and reduce the risk of injuries (Lovell, Midgley, Barrett Carter, & Small, 2013). However, if the exercise volume and intensity are too high, glycogen stores can be reduced and body temperature rises excessively, with consequent performance impairment (Gregson, Batterham, Drust, & Cable, 2005).

Concerning football, usually, the WU has been composed of activities such as: static and dynamic stretching, injury-preventive neuromuscular activities, post activation potentiating based-exercises and high-intensity short duration WU (Hammami, Zois, Slimani, Russel, & Bouhlel, 2018), among others. Nowadays, it is still not clear which method may be the best, even if some of them might be better than the others. What is clear is that the use of specific football movements has positive effects on the performance (Taher & Parnow, 2017).

Regarding the duration and the intensity, it is not clear how the pre-match WU (PMWU) should be. In previous studies, there are WU routines lasting from five minutes (Carvalho, et al., 2012) to 35 minutes (Mohr, Krustrup, Nybo, Nielsen, & Bangsbo, 2004), combining high-intensity (Zois, et al., 2015) and lower intensity preparatory exercises (Anderson, Landers, & Wallman, 2014). Concerning the duration, Yanci and collegues (2019) found that the sprint performance of the players was better after a 8-minute PMWU than after a 25-minute one. On the other hand, the systematic review by Silva and collegues (2018) revealed that PMWU time must be between 10 and 15 minutes, increasing the intensity progressively to optimize explosive performance. This increment of the intensity during PMWU was due to the higher number of accelerations and decelerations per minute in professional futsal teams (Silva, Travassos, Gonçalves, Brito, & Abade, 2020).

The inclusion of Global Positioning System (GPS) technology in the training process has made it possible to obtain objective external load (EL) information from training tasks (Martín-García, et al., 2020), sessions, training weeks (Martín-García, Gómez-Díaz, Bradley, Morera, & Casamichana, 2018), or longer periods of time such as a whole season (Anderson, et al., 2016). Recently, this technology has been applied in the study of the PMWU period of football matches, comparing the physical load during the PMWU with that recorded during the whole match (Williams, Jaskowak, & Williams, 2019). This research concludes that a PMWU amounts between 22% (≈2,000 m of TD for the soccer players) and 27% of external match load, including values of ≈25% in distance covered at sprinting (SPR).

On the other hand, it has been seen that the physical performance of a match is very different in every age and league. Senior professionals play the match at higher intensity (Buchheit, Mendez-Villanueva, Simpson, & Bourdon, 2010), partly because they have higher levels of physical fitness than young players. Relativizing the PMWU loads using the match load as a reference will allow more meaningful comparison of the different age groups, and provide a better understanding about their respective pre-match preparation.

Accordingly, the aim of this study was to compare the absolute and relative (with reference to the individual match demands) EL during PMWU in official matches between four teams of different age categories belonging to the same professional club. The results will allow to know if there is a progression in the absolute loads to which players are exposed in different age categories, in addition to knowing if all the EL variables are requested in the same magnitude with respect to the match demands.

Methods

Participants

The players who participated in this study were 96 players from different age categories of the same professional Spanish club: professional team (PRO, n=26; age: 25.1 ±4.1 years; stature: 180.2 ±6.4 cm; body mass: 74.7±6.6 kg), reserve team (RES; n=22; age: 21.2 ±1.6 years; stature: 171.4 ±38.2 cm; body mass: 72.7 ±5.9 kg), under-21 team (U21; n=28; age: 19.7 ±1.1 years; stature: 178.2 ±5.4 cm; body mass: 71.4 ±6.0 kg) and under-18 team (U18; n=20; age: 18.0 ±0.6 years; stature: 173.6 ±8.2 cm; body mass: 71.8 ±5.9 kg). The referred professional team was playing in the Spanish First League (La Liga) and regularly participated in international competitions (e.g. UEFA Europa League). The sample size was calculated with the independent power analysis program G*Power (version 3.1.9.7 for Windows, Institut für Experimentelle Psychologie, Düsseldorf, Germany). In a statistical ANOVA test for where four groups are compared, an effect size of 0.50, a probability of error α of 0.05, and a power of 0.95 (1-β) (Faul, Erdfelder, Lang, & Buchner, 2007), the total estimated sample was n=76 players (less than the 96 players recorded in the present study). The data arose as a condition of employment for the players, who were assessed on a daily basis. The club gave consent to use the information, the players gave informed consent before participating, the players' identities were anonymized and the Ethics Committee reported favorably (code: M10-2024-124).

Measures

All PMWU EL demands were monitored using GPS units. A total of eleven GPS variables were measured both in the PMWU and during the match. The variables analyzed were the total duration (minutes), total distance covered (TD, m), distance covered at moderate speed running (MSR: >14 $km \cdot h^{-1}$, m), distance covered at high speed running (HSR: >18 $km \cdot h^{-1}$, m), distance covered at very high speed running (VHSR: >21 $km \cdot h^{-1}$, m), distance covered at sprinting (SPR: >24 $km \cdot h^{-1}$, m), the acceleration load (Aload, AU), the player load (PL, AU), the number of moderate and high-intensity accelerations (ACC: >2 $m \cdot s^{-2}$, n) and decelerations (DEC: <-2 $m \cdot s^{-2}$, n), and the maximum velocity reached (Vmax: $km \cdot h^{-1}$). The intensity thresholds used have been established based on previous studies (Guridi, Catellano, & Echezarra 2021) . The velocity dwell time (i.e., minimum effort duration) was 0.5 second, the acceleration dwell time was 0.1 second and the minimum acceleration interval duration was 0.8 second. The configuration of the devices, although not usually stated in the studies, is key to interpret the data correctly (Torres-Ronda, Beanland, Whitehead, Sweeting, & Clubb, 2022).

The variable Aload is calculated by summing all accelerations and decelerations in positive, and this variable provided an indication of the total acceleration requirements of the athlete, irrespective of velocity. Previous research studies have shown an inter-unit coefficient of variation of 2-3% (Delaney, Cummins, Thornton, & Duthie, 2018) and these are lower than typically seen between devices using the traditional effort-detection-based approach to acceleration assessment (Delaney, et al., 2018). PL is an indicator based on the combined accelerations made in three planes of movement. Previous research on this indicator had reported high intra- and inter-device reliability (Boyd, Ball, & Aughey, 2011), and it had been shown to be a valid way of monitoring training load in soccer players (Casamichana, Castellano, Calleja-Gonzalez, San Roman, & Castagna, 2013).

The number of satellites used to infer GPS signal quality, horizontal dilution of precision and the average of the GNSS quality were for the PRO: 12.1±0.9 satellites, 0.9±0.3 and 65.3±8.5%; for the RES: 11.6±0.9 satellites, 0.9±0.3 and 67.1±5.3%; for the U21: 11.7±0.5 satellites, 0.8±0.1 and 68.6±4.7%; and for the U18: 11.9±0.1 satellites, 0.8±0.1 and 71.1±4.5%, respectively.

Procedures

The study was conducted in 2019-2020 competitive season. Data collection was carried out during the season, in competitive microcycles, keeping environmental conditions such as temperature and humidity similar in all records. The data were collected by experienced physical preparation managers. The weekly training routines and competitive matches were the usual competitive training microcycles carried out during the whole season. The external training load was collected using GPS devices (Vector S7 for PRO and RES and Vector X7 for U21 and U18, both by Catapult). The players were familiar with the use of GPS, as it was part of their daily routine for TL monitoring. Players wore a GPS device from the beginning of the WU until the end of the match. The GPS device was fitted to the upper back (i.e., between the shoulder blades) of each player using an adjustable neoprene harness. After each game, the data was extracted to a computer and analysed using Catapult OpenField v2.4. A total of 719 individual GPS files from PMWU data were analyzed, with the following distribution per team: PRO=106, RES=155, U21=263 and U18=195 GPS files, with an average of 4.7 ±2.9 (min=1 and max=12) observations per player. All players had to undertake at least one complete PMWU to participate in the study. Players who did not meet this criterion were withdrawn from the study.

Furthermore, the EL of the match completed by each player was calculated to compare with the demand of the PMWU. The match demand was estimated for the players who did not complete a match in the study period: a) for players who played less than 70 minutes the average EL of full matches of the player's position was taken into account and b) for players who played more than 70 minutes the EL was used to calculate the EL they would have in 94 minutes of the game.

The value of each PMWU was expressed in absolute values and relative to the mean EL registered during competitive matches:

(mean training session EL x 100) /
mean competitive-match EL.

Statistical analyses

The descriptive statistics were calculated and reported as mean and standard deviation (±SD) for each age category on each variable. Both, absolute and relative (with reference to the individual match) values were used for analysis. While the dependent variables were total duration and the 10 EL measures, independent variables were the different teams studied. The differences between age category groups in all measured variables were examined using analysis of variance (ANOVA) for independent samples. *Post-hoc* analyses were performed using Bonferroni's honestly significant difference test. Descriptive statistics for the outcome measures were calculated using mean, standard deviations and confidence interval at 95%. Cohen's d effect size was used for pairwise comparisons. Thresholds for effect size (ES) statistics were <0.2, trivial; <0.6, small; <1.2, moderate; <2.0, large; and ≥2.0, very large (Hopkins, Marshall, Batterham, & Hanin, 2009). All data analyses were carried out using *Excel* and the statistical analysis software *JASP version 0.9.2* (University of Amsterdam, https://jasp-stats.org/). The level of significance was set at $p<.05$.

Results

Absolute pre-match WU load

Table 1 presents the absolute values obtained in the PMWU across variables. The total duration was higher for PRO, U21 and U18 with respect to RES team (ES: 1.0-3.6; $p<.001$), while PRO and U18 warmed up for longer time than U21 (ES: 0.5-2.2; $p<.001$). Finally, U18 warmed up for longer time than PRO (ES: 1.5; $p<.001$).

The RES team obtained a higher accumulated load than PRO, U21 and U18 in the MSR and DEC variables (ES: 0.7-2.5; $p<.001$). U21 obtained a higher cumulative load than PRO, RES and U18 in the variables VHRS (ES: 1.0-1.3; $p<.001$), SPR (ES: 1.3-1.7; $p<.001$) and Vmax (ES: 0.9-1.8; $p<.001$). In addition, the group U18 obtained a higher cumulative load than PRO, RES and U21 in the variables total duration, PL and Aload (ES: 0.4-3.6; $p<.001$).

In the variables TD, MSR, HRS, ACC and DEC, the teams RES, U21 and U18 accumulated greater EL than PRO (ES: 0.3-2.5; $p<.001$). In the variable TD, the RES and U18 teams covered more distance than U21 (ES: 0.3-0.4; $p<.001$), and the opposite occurred in the MSR and HSR variables, where the U21 team covered more distance than U18 (ES: 0.7-1.0; p<.001). In the HSR variable, it can also be seen that the RES team covered more distance than U18 (ES: 0.9; p<.001). In the variables SPR and Vmax, the PRO and U18 teams obtained a greater accumulated load than RES (ES: 0.4-0.9; p<.001). In the variable Vmax it can also be seen that the PRO group achieved higher speeds than U18 (ES: 0.4; p<.001). In the variable PL, U21 obtained grater load than RES team (ES: 0.4; p<.001). Finally, in the DEC variable, the U18 team obtained higher number of actions than U21 (ES: 0.4; p<.001).

Figure 1 shows the significant difference between the four teams in the MSR (m) variable. All the teams covered more distance at MSR than the PRO (ES: 0.9-2.5; p<.001). Furthermore, the RES team covered significantly more distance at MSR than the U21 team (ES: 0.9; p<.001) and U18 (ES: 1.3; p<.001). Finally, the U21 team covered significantly more distance at MSR than the U18 (ES: 0.7; p<.001).

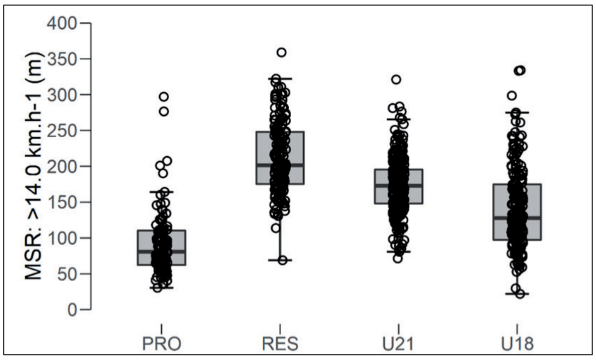

Figure 1. Comparison of distance covered at moderate speed running (MSR: >14km·h^{-1}) (m) during the pre-match warm-up between different teams in absolute terms.

Relative PMWU load

Table 2 presents the values obtained in the PMWU across variables according to the percentage of the individual match demands. The RES team obtained a higher accumulated load than PRO, U21 and U18 in the MSR (ES: 0.6-2.6; p<.001) and DEC variables (ES: 0.9-1.7; p<.001). U21 covered more distance than PRO, RES and U18 in the variables VHRS (ES: 1.0-1.1; p<.001), SPR (ES: 1.1-1.4; p<.001) and reached higher Vmax (ES: 0.8-2.0; p<.001). In addition, the group U18 obtained a higher cumulative load than PRO, RES and U21 in the variables total duration (ES: 1.4-3.8; p<.001), PL (ES: 0.3-0.7; p<.001), and Aload (ES: 1.0-1.2; p<.001).

In the variables TD, MSR, HRS, ACC and DEC, the teams RES, U21 and U18 developed greater EL than PRO (ES: 0.5-2.6; p<.001). In the total duration variable, PRO obtained a higher volume than RES (ES: 1.8; p<.001) and U21 (ES: 0.6; p<.001), while U21 accumulated longer time than RES (ES: 1.1; p<.001). In the variable TD, the U18 team covered more distance than U21 (ES: 0.4; p<.001). In the MSR and HSR variables, the U21 team covered more distance than U18 (ES: 0.8-1.0; p<.001). In the HSR variable, it can also be seen that the RES team covered more distance than U18 (ES: 0.9; p<.001). In the variables SPR and Vmax, the PRO and U18 teams obtained a greater accumulated load and reached higher Vmax than RES (ES: 0.7-1.2; p<.001). In the variable Vmax it can also be seen that the PRO group achieved higher speeds than U18 (ES: 0.3; p=.037). In the variable PL, U21 obtained grater load than RES team (ES: 0.3; p=0.007). Finally, in the ACC variable, the RES team obtained higher number of actions than U21 and U18 (ES: 0.9-1.2; p<.001).

Discussion and conclusions

The main purpose of this study was to compare the EL of the PMWU in absolute terms and as a percentage of the individual match demands in football teams of different ages belonging to an elite professional football club. The main findings of the study refer to the fact that the PRO team presents a lower level of EL in most of the variables studied, and these differences were consistent both when the external demand for PMWU was compared in absolute terms and relative to the match demands. The relative load (%) of some variables with respect to the match demands exceeded 20% of the match load (e.g., Aload), which should be assessed by the strength and conditioning coach to prevent fatigue in the players while ensuring an adequate condition of them to dispute the match.

Although PMWU has traditionally been approached as an important element in preventing football player's injuries (Soligard, et al., 2009), very little information exists regarding the EL in soccer players during PMWU. Regarding the duration, it is not very clear how the PMWU should be. In previous studies, there are reports of PMWU between five minutes (Carvalho, et al., 2012) and 39 minutes (Williams, et al., 2019). Other study (Yanci, et al., 2019) has suggested that although all protocols (warm-up duration of 25, 15 and 8 min) significantly improved the feeling of players being prepared to play the game, only the shortest improved the acceleration ability of the soccer players. In the present study, the PMWU durations ranged between ≈18-25 min, there being significant differences across all the teams. Although the club has established a protocol to carry out the PMWU, sometimes due to the dynamics proposed by the coach regarding the duration of activities and breaks, players' requests to shorten or lengthen preparatory tasks, coaching pre-instructions delaying the start of PMWU more than desired, or weather aspects (e.g., hot environment that invites to reduce the duration of the

Table 1. Comparison of external pre-match warm-up load (mean and standard deviation) between different teams in absolute terms

Teams	Total duration (minutes)	TD (m)	MSR (m)	HSR (m)	VHSR (m)	SPR (m)	Vmax (km·h^{-1})	PL (AU)	Aload (AU)	ACC (n)	DEC (n)
PRO	21.2±3.2^{bc}	1,388.4±183.8	90.9±44.4	39.5±18.9	23.7±11.9	10.5±8.4^{b}	25.5±2.3^{bd}	180.5±26.0	534.1±60.5	16.0±4.7	10.3±4.4
RES	17.3±0.6	1,600.2±144.2^{ac}	212.2±50.1^{acd}	74.7±30.3^{ad}	25.3±22.3	5.1±11.2	23.6±2.0	174.5±24.2	534.4±50.7	21.8±6.5^{a}	19.9±7.0^{acd}
U21	19.5±2.4^{b}	1,546.1±170.4^{a}	174.0±38.8^{ad}	73.6±23.8^{ad}	45.9±18.3^{abd}	29.3±15.7^{abd}	27.5±2.4^{abd}	185.8±27.4^{b}	539.6±66.9	22.5±5.0^{a}	14.1±43.0^{a}
U18	25.6±2.6^{abc}	1,612.6±197.8^{ac}	140.4±57.3^{a}	48.1±26.5^{a}	24.1±14.7	9.5±9.3^{b}	24.5±2.6^{b}	198.6±29.5^{abc}	620.5±78.7^{abc}	21.3±5.7^{a}	16.0±4.9^{ac}
F(p)	331.534 (<0.001)	42.603 (<0.001)	154.675 (<0.001)	78.182 (<0.001)	83.395 (<0.001)	169.206 (<0.001)	113.236 (<0.001)	24.734 (<0.001)	75.268 (<0.001)	36.576 (<0.001)	81.162 (<0.001)
ES	PRO-RES: 1.7 PRO-U21: -0.5 PRO-U18: 1.5 RES-U21: 1.0 RES-U18: 3.6 U21-U18: 2.2	PRO-RES: -1.3 PRO-U21: -0.9 PRO-U18: -1.2 RES-U21: 0.3 RES-U18: -0.1 U21-U18: -0.4	PRO-RES: -2.5 PRO-U21: -2.1 PRO-U18: -0.9 RES-U21: 0.9 RES-U18: 1.3 U21-U18: 0.7	PRO-RES: -1.3 PRO-U21: -1.5 PRO-U18: -0.4 RES-U21: 0.0 RES-U18: 1.0 U21-U18: 1.0	PRO-RES: -0.1 PRO-U21: -1.3 PRO-U18: -0.0 RES-U21: -1.0 RES-U18: 0.1 U21-U18: 1.3	PRO-RES: 0.5 PRO-U21: -1.3 PRO-U18: 0.1 RES-U21: -1.7 RES-U18: -0.45 U21-U18: 1.5	PRO-RES: 0.9 PRO-U21: -0.9 PRO-U18: 0.4 RES-U21: -1.8 RES-U18: 0.4 U21-U18: 1.3	PRO-RES: 0.2 PRO-U21: -0.2 PRO-U18: -0.6 RES-U21: -0.4 RES-U18: - 0.9 U21-U18: -0.5	PRO-RES: -0.0 PRO-U21: -0.1 PRO-U18: -1.2 RES-U21: -0.1 RES-U18: -1.3 U21-U18: -1.1	PRO-RES: -1.0 PRO-U21: -1.3 PRO-U18: -1.0 RES-U21: -0.1 RES-U18: 0.1 U21-U18: 0.2	PRO-RES: -1.6 PRO-U21: -0.9 PRO-U18: -1.2 RES-U21: 1.1 RES-U18: 0.7 U21-U18: -0.4

Note: TD is total distance; MSR is distance covered at moderate speed running (>14 km·h^{-1}); HSR is distance covered at high speed running (>18 km·h^{-1}); VHSR is distance covered at very high speed running (>21 km·h^{-1}); SPR is distance covered at sprinting (>24 km·h^{-1}); Vmax is maximum velocity reached (km·h^{-1}); PL is the player load; Aload is the acceleration load; ACC is the number of moderate and high intensity accelerations (>2 m·s^{-2}); DEC is the number of moderate and high intensity deceleration (<-2 m·s^{-2}); a>PRO; b>RES; c>U21; d>U18.

Table 2. Comparison of external pre-match warm-up load (mean and standard deviation) between different teams in percentage (%) of the individual match demands

Teams	Total duration	TD	MSR	HSR	VHSR	SPR	Vmax	PL	Aload	ACC	DEC
PRO	23.0±3.7^{bc}	13.3±1.8	3.8±1.8	3.9±2.1	5.0±3.0	6.3±6.2^{b}	80.2±7.8^{bd}	17.2±2.5	18.5±2.0	13.8±4.5	9.0±4.0
RES	18.4±1.0	15.0±1.2^{a}	8.8±2.0^{acd}	7.8±3.0^{ad}	5.2±3.9	2.2±4.6	72.3±5.6	17.0±2.1	18.1±1.8	19.8±5.6^{ad}	17.7±5.8^{acd}
U21	21.0±3.0^{b}	14.6±1.7^{a}	7.7±1.9^{ad}	8.3±3.3^{ad}	11.4±6.3^{abd}	22.3±17.4^{abd}	86.1±7.4^{abd}	17.8±2.6^{b}	18.4±2.3	19.0±4.2^{ad}	12.3±3.6^{a}
U18	27.7±3.2^{abc}	15.4±2.0^{ac}	6.1±2.4^{a}	5.2±2.8^{a}	6.0±4.0	7.4±8.1^{b}	77.7±8.3^{b}	18.6±2.5^{abc}	21.0±2.7^{abc}	17.4±4.5^{a}	13.2±3.7^{a}
F(p)	343.791 (<0.001)	34.966 (<0.001)	153.635 (<0.001)	80.934 (<0.001)	83.433 (<0.001)	120.732 (<0.001)	122.577 (<0.001)	14.558 (<0.001)	65.883 (<0.001)	41.299 (<0.001)	93.644 (<0.001)
ES	PRO-RES: 1.8 PRO-U21: 0.6 PRO-U18: -1.4 RES-U21: -1.1 RES-U18: -3.8 U21-U18: -2.2	PRO-RES: -1.1 PRO-U21: -0.8 PRO-U18: -1.1 RES-U21: 0.2 RES-U18: -0.2 U21-U18: -0.4	PRO-RES: -2.6 PRO-U21: -2.1 PRO-U18: -1.0 RES-U21: 0.6 RES-U18: 1.2 U21-U18: 0.8	PRO-RES: -1.5 PRO-U21: -1.5 PRO-U18: -0.5 RES-U21: -0.2 RES-U18: 0.9 U21-U18: 1.0	PRO-RES: -0.1 PRO-U21: -1.1 PRO-U18: -0.3 RES-U21: -1.1 RES-U18: -0.2 U21-U18: -1.0	PRO-RES: 0.8 PRO-U21: -1.1 PRO-U18: -0.1 RES-U21: -1.4 RES-U18: -0.8 U21-U18: 1.1	PRO-RES: 1.2 PRO-U21: -0.8 PRO-U18: 0.3 RES-U21: -2.0 RES-U18: -0.7 U21-U18: 1.1	PRO-RES: 0.1 PRO-U21: -0.2 PRO-U18: -0.6 RES-U21: -0.3 RES-U18: -0.7 U21-U18: -0.3	PRO-RES: 0.2 PRO-U21: 0.0 PRO-U18: -1.0 RES-U21: -0.1 RES-U18: -1.2 U21-U18: -1.1	PRO-RES: -1.2 PRO-U21: -1.2 PRO-U18: -0.8 RES-U21: 0.2 RES-U18: 0.5 U21-U18: 0.4	PRO-RES: -1.7 PRO-U21: -0.9 PRO-U18: -1.1 RES-U21: 1.2 RES-U18: 0.9 U21-U18: -0.2

Note: TD is total distance; MSR is distance covered at moderate speed running (>14 km·h^{-1}); HSR is distance covered at high speed running (>18 km·h^{-1}); VHSR is distance covered at very high speed running (>21 km·h^{-1}); SPR is distance covered at sprinting (>24 km·h^{-1}); Vmax is maximum velocity reached (km·h^{-1}); PL is the player load; Aload is the acceleration load; ACC is the number of moderate and high intensity accelerations (>2 m·s^{-2}); DEC is the number of moderate and high intensity deceleration (<-2 m·s^{-2}); a>PRO; b>RES; c>U21; d>U18.

PMWU or cold environment that requires a longer PMWU) may be the reason for this variability.

In absolute terms, in the current study, we found lower values of TD and SPR with respect to the study of Williams et al. (2019). These authors found that the PMWU involved 2,000 m of TD for the soccer players, representing more than 20% of the TD in the match, reaching values of more than 25% in SPR. The strategies used by the teams during the PMWU are variable and of different duration, which could explain these differences, since they spent more than 39 minutes of PMWU in the referred study (Williams, et al., 2019). In contrast, compared to the English Championship players investigated by Hills et al. (2020), in our study teams had very similar absolute TD (≈1,500 m) and ACC values and higher MSR, HSR, SPR, PL and DEC values at shorter PMWU durations. Moreover, in a previous study with futsal players (Silva, et al., 2020), the players covered shorter absolute TD in the warm-up (≈1000 m). It is necessary to consider that the court size in a futsal match is smaller than in soccer match (for instance in total distance), since the duration of the match is shorter.

In the comparison of the analysed teams, the results show that each team prioritizes a type of movement, obtaining higher values in certain EL parameters. The PRO team presents the lowest values in many of the EL variables studied (e.g., TD, HSR or ACC), while the U18 obtained the highest values in the global EL variables (e.g., PL and Aload) and U21 in the high-speed variables (i.e., VHSR and SPR). Probably as a habitual consequence of congested calendar periods or a better knowledge of the individual needs of professional players, they try to make the performance carried out as efficient as possible. On the other hand, the variability among teams may be due to the different dynamics proposed by the physical condition coaches. It may also be conditioned by contextual factors (e.g., weather, time available, proximity between facilities), so it could be interesting to pay special attention to the said activity with the double objective of optimizing while not compromising performance in a competition. As it is known (Hills, et al. 2020), a well-designed warm-up routines could optimize match performance and the duration of the warm-up could be important to be accounted for (Yanci, et al., 2019). In this sense, clubs should regulate this type of intervention between the teams under their responsibility, trying to optimize them.

The comparison of demands expressed in terms of the percentage of the match demand has been an analytical strategy used in recent years. Thus, the intensity of the training tasks (Martín-García, et al., 2020), the load of different training sessions of a microcycle (Martín-García, et al., 2018) or the accumulated load of the training sessions have been analysed under this perspective making comparisons of positions (Baptista, Johansen, Figueiredo, Rebelo, & Pettersen, 2019) or by differentiating between starters and non-starters (Stevens, de Ruiter, Twisk, Savelsbergh, & Beek, 2017). In our study, the differences between the teams are hardly modified when the values are expressed in absolute terms or according to the match demands (%). This may be because the competition demands do not differ too much between teams of different age groups in the adulthood (Dellal & Wong, 2013), a scenario that differs when players are younger (Buchheit, et al., 2010). The EL of the PMWU represents a variable percentage depending on the external variable chosen with respect to the match, ranging from ≈5% for distances covered at high speed (HSR: >18 $km \cdot h^{-1}$ and VHSR: >21 $km \cdot h^{-1}$) to ≈20% (e.g., SPR for U21 or Aload for U18). It seems interesting that load variables such as PL, Aload, ACC and DEC represent a load of ≈15-20% with respect to the match demands. Instead, high-speed variables such as HSR, VHSR and SPR represent around ≈5-10%, although the average of the percentage of the variables was around 15% of the match load. Systematic and efficient training should ensure that players are prepared to compete, reducing the adverse effects of possible previous fatigue.

Sprint actions are one of the most frequent mechanisms of hamstring injury (Schuermans, Van Tiggelen, Palmans, Danneels, & Witvrouw, 2017). Although the occurrence of near-to-maximal speed-running bouts in elite soccer are not so frequent (Buchheit, Simpson, Hader, & Lacome, 2021), several studies have appeared in recent years advocating the need to manage this type of high intensity action on a weekly and monthly basis, reducing the likelihood of injury through stable over time and moderate stimulation (Colby, et al., 2018). However, to date, there is only one investigation that shows the maximum speed reached by football players during PMWU in absolute terms (Hills, et al., 2020). The peak speed achieved in the teams studied were higher (23.6-27.5 $km \cdot h^{-1}$) than (19.5 $km \cdot h^{-1}$) in the previous research study (Hills, et al., 2020). However, there is no information regarding the maximum speed relative achieved in PMWU in respect to the match demands. In this regard, the present study shows that the maximum speed reached by players during PMWU is between 70 and 90% of the individual maximum speed. Since match players reach values close to their individual maximum speed (Sparks, Coetzee, & Gabbett, 2017) and based on the high levels of muscle activation required in a sprint action (Ross, Leveritt, & Riek, 2001), it seems necessary to reach a high percentage of the individual maximum speed during the PMWU activity. The importance of preparing the player for this type of effort is mainly due to the fact that it is not known if the first action at the start of the match will require this type of activity carried out at maximum speed, given that the first 15 minutes of matches are usually the most demanding (Bradley, et al., 2009).

Nowadays, although there is the possibility of using GPS devices during professional football matches, many teams monitor their players' activity through video-tracking systems. These video-tracking systems do not provide information on the activity of players during the PMWU. Taking into account that there are variables with PMWU loads close to 5-20% of a match effort, it seems interesting to register this load in order to estimate the values accumulated by the player during the microcycle, mesocycle or for the calculation of some training load indicators such as training monotony or strain (Clemente, et al., 2020) or the assessment of week-to-week changes in training load aside from a total training load (Gabbet, 2016).

Among the main limitations of the study, we can state that no internal load variable of the players was included. This would have allowed a better understanding of how external demand provokes a particular internal response in each player. Furthermore, having a detailed analysis of the positions would have made it possible to assess whether the activities or tasks proposed in the PMWU provides appropriate stimulation for players in different positions. Future research should include proposals to overcome the limitations of this study.

The main conclusion of the study is that during the PMWU there are some variables with loads close to 15-20% of the match load. For this reason, it seems interesting to take into account this EL in order to estimate the values accumulated by the player during the workload monitoring cycle. On the other hand, the variables that are most activated during the PMWU are PL and Aload, unlike the VHSR and SPR, which are the least demanded, so they never reach maximum speed. Finally, the PRO team presents the lowest values in many of the EL variables studied (e.g. TD, HSR or ACC), perhaps because experience allows them to fine-tune the requirements and that the warming-up is effectively carried out with a minimum energy cost.

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THE EFFECTS OF ATTENTIONAL FOCUS INSTRUCTIONS ON THE PERFORMANCE OF A PERSISTENT FORM-BASED SKILL IN GYMNASTICS

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Abstract:

External relative to internal focus instructions have been shown to be more effective for enhancing optimal performance across various motor tasks that do not rely on movement quality or movement form. The aim of this study was to examine the effects of an external versus an internal focus of attention on the motor performance of a gymnastic skill that requires static strength and movement form. Participants with previous experience in aerobic gymnastics were asked to perform an L-support task for 4 seconds in three attentional focus conditions: internal focus, external focus, and control, with the order counter-balanced across focus conditions. Two pieces of yellow tape (2×9 cm) were attached to the gymnasts' feet on the inner side of the navicular bones. Two pieces of red tape (2×9 cm) were wrapped around the distal phalanx of the big toes of the right and left foot. All participants performed four trials in the external focus (focus on keeping red tape below the yellow tape), internal focus (focus on pointing your toes), and control (no-focus) conditions. The results showed that execution faults were smaller in the external focus condition compared to the internal focus and control conditions. No difference was found between the internal focus and control condition. The findings of this study indicate that the external focus is more beneficial than the internal focus and no-focus control condition for enhancing the performance of a static gymnastic skill that requires static strength and movement form.

Keywords: *focus of attention, movement form, motor performance, gymnastics*

Introduction

Effective and efficient verbal communication between the coach and athlete is crucial for optimising motor performance. In this regard, coaches aim to provide purposeful and appropriate verbal instructions with respect to movement techniques, which subsequently could enhance the performance and learning of a new motor skill. These verbal instructions have the potential to direct the attentional focus of performers to the important and relevant aspects of the motor task, either internally or externally (Wulf, 2007). An external focus is defined as the performer's attentional focus on movement effects or movement goals, such as elements outside the body, implements, surfaces, a target, and/or the trajectory of an object or the task goal. In contrast, an internal focus reflects a performer's attentional focus on body movements such as arms, hands, feet, or toes. Ample research has adequately shown that an external focus is more beneficial than an internal focus across various motor tasks (Chua, Jimenez-Diaz, Lewthwaite, Kim, & Wulf, 2021; Wulf, 2013). Yet, little research has been conducted on motor skills that require a combination of dynamic or static strength and movement form (Abdollahipour, Wulf, Psotta, & Palomo Nieto, 2015; Guss-West & Wulf, 2016; Lawrence, Gottwald, Hardy, & Khan, 2011). Therefore, the aim of the current research was to examine the effectiveness of attentional focus instructions on the motor performance of a gymnastic motor skill that requires static strength and movement form.

Recent meta-analyses and reviews have reported the consistent superiority of an external relative to an internal focus of attention across various outcome measures, motor tasks, ages, (dis)ability ranges, and expertise levels (Chua, et al., 2021; Simpson, Ellison, Carnegie, & Marchant, 2021). Largely, the outcome measures utilised in these studies have relied upon outcome measures such as performance accuracy, movement time, stability/deviations in balance, distance, or amount of force production. For instance, studies have shown the advantages of an external relative to an internal focus in performance accuracy in golf putting task, dart-throwing task, two-handed catching of tennis balls, and playing the piano (Abdollahipour & Psotta, 2017; An, Wulf, & Kim, 2013; Duke, Cash, & Allen, 2011; Lohse, Sherwood, & Healy, 2010; Marchant, Clough, & Crawshaw, 2007), movement time such as riding a pedalo or swimming (Freudenheim, Wulf, Madureira, Pasetto, & Corrěa, 2010; Stoate & Wulf, 2011; Totsika & Wulf, 2003), force production such as pressing barbell (Marchant, Greig, Bullough, & Hitchen, 2011), distance such as vertical jump-and-reach task, standing long-jump task (Porter, Ostrowski, Nolan, & Wu, 2010; Wulf, Dufek, Lozano, & Pettigrew, 2010), or stability/deviations in balance on a stabilometer, ski-simulator, or a rubber disk task (Wulf, Höß, & Prinz, 1998; Wulf, Mercer, McNevin, & Guadagnoli, 2004; Wulf, Shea, & Park, 2001; Wulf, Weigelt, Poulter, & McNevin, 2003). As posited by the constrained-action hypothesis, a possible explanation for the advantages of an external focus is that an external focus promotes an automatic mode of motor control, whereas an internal focus degrades movement automaticity. More recent explanations propose that an external focus promotes goal-action coupling, which consequently enhances performance outcomes (Abdollahipour, Palomo Nieto, Psotta, & Wulf, 2017; Abdollahipour, Land, Valtr, Banátová, & Janura, 2023; Wulf & Lewthwaite, 2016). As such, an external focus is shown to be more effective than an internal focus in various motor tasks and contexts with respect to outcome measures such as performance accuracy, movement time, stability in balance, or force production.

Nonetheless, only a few studies have been carried out on attentional focus effects whereby the quality of movement form is of primary consideration (Abdollahipour, et al., 2015; Guss-West & Wulf, 2016; Lawrence, et al., 2011). Moreover, the gymnastic skills examined have been dynamic in nature. Initially, Lawrence et al. (2011) did not find any benefits for an external focus ("focus on the movement pathway and on exerting an even pressure on the support surface") relative to an internal focus ("focus on exerting an equal force on their feet, keeping their arms out straight, level with their shoulders") when comparing movement form during the performance of a complex series of gymnastic routines (e.g., starting position, a lunge, an arabesque, a full turn, and a finish position). However, these instructions were confounded or irrelevant to particular aspects of the routines. Indeed, attentional focus instructions did not adequately apply to all the movements the participants were required to do (e.g., a full turn). Next, Guss-West and Wulf (2016), using a survey analysis, reported that professional ballet dancers use more external focus cues, including metaphors and images such as "stretching like a star in all directions", "climbing up a corkscrew" or "jumping over a lake" when performing elements like an arabesque, pirouette, or a grand jeté, respectively. Likewise, Abdollahipour et al. (2015) also examined a gymnastic element requiring temporary movement form. Having attached a tape marker to the chest, gymnasts were asked to perform a jump and ½ half-turn task. While airborne, participants were instructed to focus on the direction in which "the tape marker" (external focus) or "your hands" (internal focus) are pointing after the half-turn. The findings suggested superior movement form and greater jump height in the external focus as compared to the internal focus or no-focus conditions. While current evidence points to the benefits of external focus for gymnastic elements that require dynamic strength, there is a clear need to advance research for examining the influence of attentional focus on motor performance or learning of motor skills that require static strength and movement form.

Therefore, the goal of the current research was to examine the effects of an internal versus an external focus of attention on motor performance in a task that requires static strength and movement form in gymnastics. We used simple and straightforward instructions by directing attention to a clear external focus cue (e.g., tape) or internal focus cue (e.g., toes) to avoid possible confounds or confusion for the gymnasts (cf., Lawrence, et al., 2011). Specifically, the current study examined the effects of attentional focus on the motor performance of an L-support gymnastic element, which is an isometric strength task and requires not only balance and strength but also movement form. We hypothesised that an external focus would be more effective (i.e., lower execution deductions) than an internal focus or control condition for enhancing movement form.

Methods

Participants

Twelve female gymnasts aged 9 to 22 years (*M*age = 14.70 ± 4.98 years), participated in the present study. All participants were experienced healthy aerobic gymnasts, with an average training experience of $M = 9.58 \pm 4.77$ years. They were recruited from an aerobic gymnastics club in Prague, Czech Republic. As previous research on the effectiveness of attentional focus on movement form in gymnastics has produced results with a large effect size (Abdollahipour, et al., 2015), we also assumed a large effect size when performing power analysis. As such, a power analysis with G*Power 3.1 indicated that 12 participants would be sufficient to identify significant differences between attentional focus conditions in a within-participants design with a power (1−β) of .80, a large effect size f of .4 ($\eta p^2 = .14$), the number of measurements = 3, correlation among repeated measures = .50, nonsphericity correction $\varepsilon = 1$, and an α level of .05 (Faul, Erdfelder, Lang, & Buchner, 2007). Informed consent was collected from all participants or their legal delegates before data collection. Their current training programme consisted of 3-5 sessions of 2-3 hours per week. Most participants had experience competing at the Czech national level. Participants were not aware of the particular objective of the study.

Task and apparatus

The task was to hold the position of L-support, an aerobic gymnastic element, on a mini portable parallel bar. The element's beginning position is sitting with legs near one another, and hands put along the side of the body near the hips. The two arms uphold the body with just the hands in contact with the smaller portable parallel bar. Hips are flexed, and legs should be held parallel to the floor throughout the task (see Figure 1). Participants were barefoot. The skill required not only isometric strength of the hip flexors, *musculus rectus femoris*, *abdominals*, and *obliques* but also balance and high precision (alignment, feet, toes, and back position), as any imperfection is taken into account as a deduction (see Table 1). The height of the mini portable parallel bar was 25 cm. The width of the parallel bar was 22 cm, and its length was 35 cm.

The experiment was conducted in a quiet room with dimensions of 4×5 m^2. All trials were recorded by two video cameras that were mounted onto tripods. One camera was set up on the diagonal front side of the participants and the second one on the left side of the mini portable parallel bar, both at a 1-meter distance. The purpose of the recordings was to help the two gymnastic international level specialists to check the execution scores of particular trials in case there was more than 0.1 difference between the two raters. Two pieces of yellow tape (2×9 cm) were attached to the gymnasts' feet on the inner side of the navicular bones. Two pieces of red tape (2×9 cm) were wrapped around the distal phalanx of the big toes of the right and left foot (see Figure 2). The tape was attached to the participants in all conditions but only served as the attentional cue in the external focus condition.

Figure 1. Schematic L-support motor task.

Figure 2. External cues represented by red and yellow tapes.

Procedure

The participants were asked to be barefoot at the beginning of the experiment as coloured tape was applied to their feet. Next, they were instructed to look at one picture representing the L-letter shape and an L-support technical representation (see Figure 3) provided by the Fédération Internationale de Gymnastique (FIG, 2009). A verbal summary of the task was given by the experimenter as the

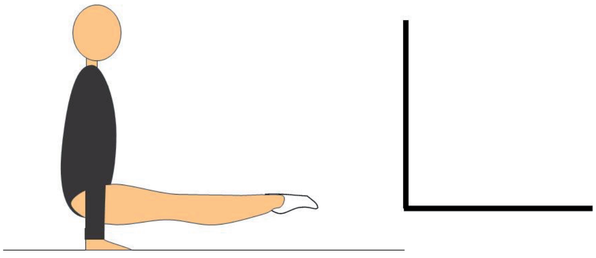

Figure 3. L-letter shape and L-support technical representation.

Table 1. General and specific execution points from the Fédération Internationale de Gymnastique code of points for aerobic gymnastics (FIG, 2009)

Execution faults	Judging criteria	Small	Medium	Large	Unacceptable
		0.1	0.2	0.3	0.5
Incorrect body alignment	Upper body position, arms and shoulders placement and neck relative to the spine	1 part	2 parts	3 parts	4 parts or more
Incorrect body form	L-shape body form, back and legs position with hips flexed at 90°	1 part	2 parts	3 parts	4 parts or more
Legs not parallel to the floor	Positioning of the legs parallel to the floor throughout the task	10°	20°	30°	40°
Legs/ feet bent	Positioning of the feet relative to the knees and hip joint	< 5 cm	5-10 cm	10-15 cm	> 15 cm
Legs/ feet apart	Feet have to be together throughout the task	< 5 cm	5-10 cm	10-15 cm	> 15 cm

participant was viewing the pictures. The verbal description included the L-position with the legs held above the floor, and the back was straight and aligned with the head upright. This information was identically presented to all participants. Participants were familiar with the task as they were experienced gymnasts.

After receiving the instructions, participants completed a practice trial. Subsequently, all gymnasts performed four trials in each of the external focus (EF), internal focus (IF), and control (Con) conditions in a counterbalanced order. The requirement was to hold the L-support for four seconds. Rest intervals of 20 seconds were provided between trials and 3 minutes between focus conditions. During the 20-second break, participants were given relevant instructions, depending on which condition was coming next. In the external focus conditions, participants were asked to "focus on keeping the red tape below yellow the tape", which helped the athletes to straighten their feet/toes without focusing on them. In the internal condition, participants were instructed to "focus on pointing their toes", which is a typical instruction in gymnastic training for straightening the feet/toes. No focus instructions were given in the control condition.

After completing four trials in each attentional focus setting, a manipulation check was used. Participants were asked at the end of every 4 trials: "What did you focus on?". The participants were asked to indicate, on a scale from 1 (not at all) to 10 (very much), "How much did you focus on…?". At the end of all 12 trials under the 3 focus conditions, the participants were asked to indicate the level of task difficulty on a scale from 1 (not at all) to 10 (very much). No input on their results was explained to the participants. At the end of the experiment, the investigators thanked the gymnasts for participating in this study.

Statistical analysis

Dependent variables

The dependent variable was represented by the participants' motor performance, indicated by the average execution scores on movement form in each attentional focus condition. Each rater assessed each L-support execution according to general and specific execution points indicated in the FIG (2009) for aerobic gymnastics (see Table 1). Principally, deductions were added for uncontrolled feet, legs/feet bent or apart, incorrect body alignment, rounded back position, and legs not parallel to the floor (see Table 1). The judges' scores for each trial were promoted as a measure of movement form. The judges then compared their performance execution error scores and found a compromise where there was an inconsistency. For each mistake, execution deductions were listed as follows: small error = 0.1, medium error = 0.2, major error = 0.3, and/or unacceptable error = 0.5 (see Table 1).

Data analysis

L-support execution scores were averaged across 4 trials and analysed using a one-way analysis of variance with repeated measures on the attentional focus conditions: (EF, IF, Con). The assumptions of normality were tested using the Shapiro-Wilk test. The data were normally distributed for all attentional focus conditions ($p>.05$). Mauchly's test was used to test the assumption of sphericity ($\chi^2(2) = 4.340$, $p=.114$). The Bonferroni test and adjustments were used in all *post-hoc* comparisons. Estimates of effect size were calculated using two measures. First, partial eta squared (ηp^2) was utilised where $\eta p^2 = .01$, $.06$, and $.14$ were estimated for a small, moderate, or large effect, respectively (Lakens, 2013). Cohen's *d* was employed as a measure of the difference between focus conditions in within-subject designs that also considers the correlation between the two means (Morris &

DeShon, 2002). The evaluation of Cohen's *d* corresponded to low (*d* = 0.2), medium (*d* = 0.5), and large (*d* = 0.8) effects (Cohen, 1998).

Inter-rater reliability in assessing the movement execution scores between two judges was determined using intra-class correlation (ICC) analysis based on a two-way mixed-effects, absolute agreement parameters (Shrout & Fleiss, 1979). The coefficient values of <.50, .50-.74, .75-.90, and >.90 were indicating poor, moderate, good, and excellent correlation, respectively (Portney & Watkins, 1993). A non-parametric Friedman test was used to compare the intensity of foci among the attentional focus conditions. The Kendall's *W* values were used for reporting the effect sizes of Friedman test ranging from 0 (indicating no relationship) to 1 (a perfect relationship). The level of significance was set at α=.05 for all statistical tests. Data analysis was provided with IBM SPSS Statistics (Version 21 for Windows, IBM, Armonk, NY, USA).

Table 2. Participants' responses to the questions in %, "What did you focus on?" in per cent, and "How much did you focus on it?" (Likert scale from 1 to 10) in different attentional focus conditions

	Control		Internal focus		External focus	
	"What did you focus on?"	"How much …?"	"What did you focus on?"	"How much …?"	"What did you focus on?"	"How much …?"
Reported external foci						
Red tape below yellow tape	-	-	-	-	50.00	8.50
Red tapes being together	-	-	-	-	8.33	8.00
Red tapes	-	-	-	-	8.33	9.00
Tapes together	-	-	-	-	8.33	7.00
Tapes together and red below yellow tape	-	-	-	-	8.33	8.00
On holding L-shape/L-support	16.67	7.50	-	-	-	-
Total	16.67	-	-	-	83.33	-
Average	-	7.50	-	-	-	8.10
Reported internal foci						
Feet together and pointing toes	8.33	10.00	25.00	8.33	-	-
Pointing tips of toes	8.33	9.00	16.67	8.50	-	-
Tips of toes	-	-	25.00	9.00	8.33	3.00
Keep the legs together and keep them in the air	-	-	8.33	9.00	-	-
Straight body	-	-	8.33	4.00	-	-
Straight legs and body	8.33	9.00	-	-	-	-
Legs and back	-	-	8.33	10.00	8.33	10.00
Feet together	8.33	9.00	-	-	-	-
Feet	-	-	8.33	8.00	-	-
On lifted legs	8.33	8.00	-	-	-	-
Rise legs a bit up	8.33	5.00	-	-	-	-
Contracting abdominal	8.33	10.00	-	-	-	-
Straight back and pointing tips of toes	8.33	9.00	-	-	-	-
Straight legs	8.33	8.00	-	-	-	-
Total	75.00	-	100	-	16.67	-
Average	-	8.56	-	8.12	-	6.50
Other foci						
Not to sit on the bar	8.33	9.00	-	-	-	-
Pass	-	-	-	-	-	-
Nothing	-	-	-	-	-	-
Total	8.33	-	-	-	-	-
Average	-	9.00	-	-	-	-

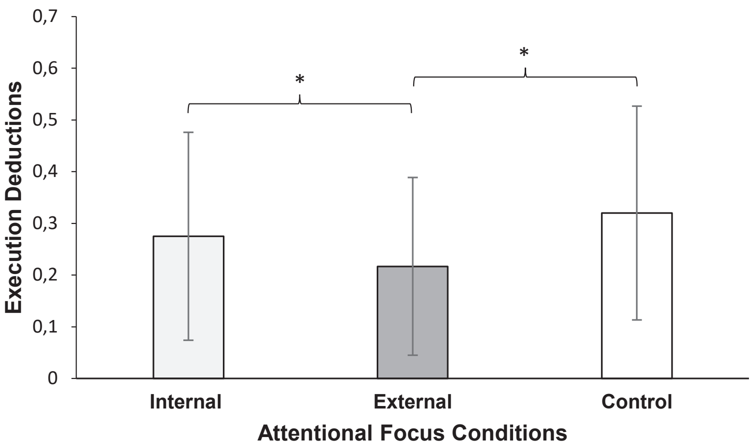

Figure 4. Mean execution scores for movement form in attentional focus conditions.

Results

Manipulation check

Participants' responses to the questions in the manipulation check indicated that the gymnasts adhered to the external and internal focus instructions to a great extent (see Table 2). Although some participants reported using other foci, most of those cues were external or internal in the external focus versus internal focus conditions, respectively. In the control condition, a relatively large proportion of cues were internal in nature. The ratings on the "intensity" of foci "How much did you focus on…?" were relatively high, with an average rating of 8.3 ± 1.66 for the internal focus, 8.0 ± 1.90 for the external focus, and 8.4 ± 1.50 for the control conditions (see Table 2). There was no significant difference among different focus conditions in intensity of foci, $\chi^2(2) = 0.619$, p=.734, Kendall's W = .026. Participants reported the level of task difficulty as medium, with an average rating score of 4.66 ± 2.09 out of 10.

Inter-rater reliability

The average measure ICC for execution scores in all trials was r=.905, 95% *CI* (.807, .931), p<.001, indicating excellent inter-rater reliability between the two judges.

Movement form

Figure 4 shows the mean execution scores for movement form across trials under the different attentional focus conditions. The results revealed that the main effect of attentional focus condition, $F(2, 20) = 14.76$, p<.001, $\eta p^2 = 0.57$, was significant. Bonferroni *post-hoc* test showed that the execution scores for L-support in the EF (M = 0.21 ± 0.17) were significantly better than in the IF (M = 0.27 ± 0.20, p=.002 d = 1.27) and control (M = 0.32 ± 0.20, p=.002, d = 0.96) conditions. No significant differences were observed between the IF and control condition (p=.196, d = 0.43).

Discussion and conclusion

The findings of this study highlight the advantage of an external focus over an internal focus and no-focus instructions condition in a static-strength gymnastic motor skill that emphasises movement form. These findings are consistent with previous studies, which have shown that gymnasts benefited from the external focus compared to the internal focus of attention in temporary form-based elements such as jump and ½ turn in gymnastics (Abdollahipour, et al., 2015). Also, the current finding is in line with previous studies that have shown the advantages of the external over the internal focus of attention in the motor tasks that do not have a clear focus cue, such as swimming (Stoate & Wulf, 2011). Overall, the findings support the notion that the immediate beneficial effects of external focus instructions on corrections of movement forms could be expanded to those motor tasks that require static strength in gymnastics.

The absence of effects for an external relative to an internal focus instruction in the study by Lawrence et al. (2011) might be related to the complexity of the task (e.g., five-part gymnastic floor routine) and the content of instructions (Abdollahipour, et al., 2015). For instance, external focus instructions related to "focusing on the movement pathway and on exerting an even pressure on the support surface". On the other hand, the internal focus instructions were related to "focusing on exerting an equal force on their feet, keeping their arms out straight, level with their shoulders" (Lawrence, et al., 2011, p. 434). Essentially, to compare the effectiveness of attentional focus instructions on motor performance, it has been recommended that the differences in the content of instructions should only be one or two words (Abdollahipour, et al., 2015; Wulf, 2013). Also, the content of attentional focus instructions, in essence, should be relevant to the task goal. When external attentional focus instructions are vague, long, and irrelevant to many aspects of the motor task, the effect may not manifest (Abdollahipour, et al., 2015; Lawrence, et al., 2011). Our findings follow existing evidence that has shown only 1- or 2-word differences in attentional focus instructions (e.g., the marker versus hands) was enough to trigger the effect, as demonstrated in prior studies (Abdol lahipour, et al., 2015).

Also, the findings of the current study indicated that while there was no difference in performance outcome between the internal and control conditions (when no instruction was given), the external focus of attention was better than the control condition. This finding is identical to the finding of a previous study on a jumping gymnastic element (Abdollahipour, et al., 2015), as movement form was enhanced in the external focus compared to the control condition. The results of the post-interview questionnaire showed that the majority of participants in the control condition (when no particular focus instruction was given) tended to focus on their body movements (Land, Tenenbaum, Ward, & Marquardt, 2013; Pascua, Wulf, & Lewthwaite, 2015; Porter, et al., 2010). That is, the participant's thinking process in the control condition is to some extent identical to the internal focus condition, specifically in the movement form-based elements (Abdollahipour, et al., 2015). Therefore, it could be suggested that when no focus instructions are given, participants have a natural tendency to focus internally on movement technique. This may be especially true for motor tasks in which the quality of the movement is the outcome of interest.

From a mechanistic standpoint, directing attentional focus at body-related movements or execution techniques induces the internal focus of attention that produces excessive self-concentration and may disrupt the automaticity of movement control, which transmits noise to the motor system, leading to blockage of optimal motor skills execution (McKay, Wulf, Lewthwaite, & Nordin, 2015; Wulf, et al., 2001). The external focus of attention, on the other hand, promotes more automatic methods of motor control by reducing conscious attentional demands and promoting goal-action coupling (Abdollahipour, et al., 2017, 2023; Wulf & Lewthwaite, 2016). More specifically, an external focus promotes functional connectivity among task-relevant motor networks that is typically observed in expert performers and, presumably, more permanent neuroanatomic changes (structural connectivity) that underlie the translation of goals into actions (Singh, Shih, Kal, Bennett, & Wulf, 2022; Wulf & Lewthwaite, 2016).

Apart from the traditional mechanistic account of the benefits of the external focus, an alternative interpretation may be found in the role that external focus plays in reducing fatigue experienced during static strength-based tasks. Research has shown that the external focus is more beneficial than the internal focus as rates of perceived exertion increase (Lohse & Sherwood, 2011). This could be due to greater movement efficiency and neuromuscular coordination associated with the external relative to the internal focus. Indeed, numerous studies have demonstrated reduced EMG activity, heart rate, oxygen consumption, cortical activity, or corticospinal modulation (see EMG meta-analysis by Chua, et al., 2021). Therefore, the enhanced efficiency of the motor system with the external focus likely facilitated the performance of the L-support task and enabled participants to maintain their movement form. In contrast, the internal focus of attention would promote focus on bodily movements, thus leading to greater awareness of fatigue, leading to more performance errors and reduced effort. However, future research with this or similar tasks should include some of the measures mentioned above in a larger sample.

Practical application

The current findings have practical applications for coaches and trainers who teach motor skills that require movement form but do not have a clear focus cue. That is, for correcting movement patterns and improving techniques in form-based motor skills such as gymnastics, ballet, or synchronised swimming, a set of external focus cues (e.g., tape), may be an efficient way to improve movement quality (Abdollahipour et al., 2015; Guss-West & Wulf, 2016). As such, trainers of motor skills or sports that do not involve an implement or do not have a clear focus cue are advised to create task-relevant and effective external focus cues, which are in the direction of the movement goal.

Limitations and future directions

Although our findings showed immediate benefits of the external relative to the internal focus instruction on motor performance, it would be interesting to examine the effectiveness of attentional focus instructions on form-based motor skills in long-term motor learning tests (e.g., retention and transfer). In addition, it would be worthwhile to examine if the benefits associated with promoting external focus of attention using an external cue or metaphors or mental images on movement goal are still valid during retention or transfer tests.

The results of the current study showed that the external relative to the internal focus instructions enhanced motor performance of a static strength motor skill that requires movement form. That is, with having fewer execution faults, external focus instructions promoted immediate motor performance of a gymnastic element (i.e., L-support) that requires high precision and static hold. Overall, an external relative to an internal focus could also be beneficial for motor tasks that do not use a clear external focus cue and are evaluated based on the quality of the movement (Abdollahipour, et al., 2015).

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Conflict of interest

The authors report no conflict of interest.

QUANTIFYING WITHIN-MATCHES TACTICAL BEHAVIORS USING POSITION DATA AND NOTATIONAL ANALYSIS IN SOCCER: THE EFFECT OF GOAL SCORING

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Abstract:

This study aimed to compare the collective and individual tactical positional behavior before the first goal was scored or conceded in official soccer matches. The sample comprised 50 players and 27 official matches played in Brazil during the 2020 and 2021 U-20 seasons. Global Positioning System devices were used to monitor the players' positional data. Collective – width, length, length per width ratio, and stretching index – and individual – spatial exploration index – variables were calculated and compared between the contextual scenarios by a one-way ANOVA. Results indicated a reduction in the width after scoring a goal (p=.006) and a lower spatial exploration after conceding a goal (p<.001) compared with the draw condition. Therefore, it is concluded that goal-scoring affects the tactical positional responses of the players. Specifically, a higher width concentration, characteristic of defensive tactical behavior, is observed after scoring a goal to keep the current match status. On the other hand, players present difficulties in exploring the space after conceding a goal. The knowledge of these intrinsic game dynamics is helpful for coaches in preparing the strategies to explore changes due to goal scoring in official matches.

Keywords: *football, youth sport, GPS devices, ecological dynamics*

Introduction

Match analysis in team sports, specifically tactical performance analysis, has evolved in recent years due to the number of available statistics and instruments. Current approaches to tactical performance analyses in soccer adopt position data (Low et al., 2020; Memmert, Lemmink, & Sampaio, 2017; Rein & Memmert, 2016) which might be captured by electronic tracking position systems (ETPS) (Bastida-Castillo, Gómez-Carmona, de La Cruz Sánchez, & Pino-Ortega, 2019; Forcher, Altmann, Forcher, Jekauc, & Kempe, 2022; Linke, Link, & Lames, 2018), such as optical-based systems and global positioning system devices (GPS). Although data from these technologies were initially adopted almost exclusively to analyze the external load of game-based activities – the distance covered at different speed zones, for example – it has been recently proposed that the position of the player on the pitch accounts for the tactical space management (Praça, Andrade, Bredt, Moura, & Moreira, 2021; Rein & Memmert, 2016). Therefore, positional data may be used to analyze how players and teams deal with spatial occupation to generate advantages that might increase the winning chance (Praça, Moreira, et al., 2021). Indeed, a recent study showed that positional data from GPS devices showed higher reliability than data provided by observational instruments (Praça, Abreu, Rochael, & Moreira, 2022), which might indicate the potential of such an approach for match analysis in soccer. The current study will use positional data to describe tactical behavior within matches based on this rationale.

In previous studies, GPS devices have often been employed to analyze soccer matches, aiming to understand how contextual factors and player positions influence game outcomes. For instance, research has indicated that older players exhibit different spatial positioning tendencies than younger players, especially when playing away (Praça, Moreira, et al., 2021). Another study showed that playing away – match venue effect – reduced the position of the offensive line (Santos, Lago-Peñas, & García-García, 2017). However, most of these studies have focused on collecting data for the entire match, overlooking the potential variations in behavior during different phases of the game. Recent research has highlighted that offensive and defensive tactical behaviors can differ significantly when considering specific game phases (Moura, Martins, Anido, de Barros, & Cunha, 2012; Praça, Moreira, et al., 2022). Therefore, considering the whole match in the tactical analysis might bias the interpretation as the reported pattern is usually the average pattern – that might not represent a specific moment within the game. The current study will shed light on this problem by splitting positional data before and after goal-scoring.

The literature extensively addresses the influence of goal scoring on players' behavior and outcomes in a match. For example, from a broader view, the simple occurrence of a goal might enhance the odds of another goal being scored over time (Nevo & Ritov, 2013). Also, scoring first might increase the winning probability, irrespective of the match venue (Caballero, Garcia Rubio, & Ibáñez, 2017). Furthermore, when analyzing the players' behavior, another study suggested that the first goal influences teams' physical responses (O'Donoghue & Robinson, 2017). On the same topic, forwards were reported to have increased physical response in winning scenarios, while defenders showed higher distances covered at high speeds in the other match statuses. (Redwood-Brown, O'Donoghue, Robinson, & Neilson, 2017).

Regarding technical-tactical variables, it has also been shown that increasing the goal difference increases the passing accuracy (Redwood-Brown, O'Donoghue, Nevill, Saward, & Sunderland, 2019), which might indicate that winning teams tend to find more space due to the attempts of the opposing team to draw the match. Besides the abovementioned results on physical and technical-tactical variables, to our knowledge, no previous study examined the impact of scoring a goal on individual and collective tactics within a match. For example, teams might adopt a more defensive tactical positioning after scoring a goal to prevent conceding a goal. This hypothesis, however, has not been tested before.

Collecting data on how contextual factors affect players and teams throughout a match provides valuable insights for sports professionals. Firstly, this information can be instrumental in designing more effective training exercises that closely mimic the demands of real match situations. Additionally, comprehending the dynamics of a match is essential for coaches to make strategic adjustments in response to anticipated influences of these contextual variables. For example, this understanding can help coaches prepare tactical alternatives for scenarios where the team either concedes a goal or scores. With this rationale in mind, the current study's primary objective was to compare individual aspects, such as spatial exploration, and collective factors, such as length, width, length-to-width ratio (LPW ratio), and the stretching index. These factors were examined in two distinct contexts: moments preceding a goal and moments following a goal in favor of the team or against the team.

Materials and methods

Participants

The sample of this study comprised the 27 matches played by a U-20 elite Brazilian soccer club over the 2020 and 2021 competitive seasons. All the matches were played in the national championship, the most relevant competition in the country. Over these matches, 50 U-20 players (19.08 ± 0.61 years, 71.13 ± 8.03 kg, 172 ± 0.03 cm, 9.61 ± 2.01 % of body fat) effectively participated. All the players consented to participate in the study. The local Ethics committee approved the study (CAAE 19596019.9.0000.5149).

Procedures

This study followed a cross-sectional retrospective design in which players' and teams' behaviors were analyzed throughout a competitive season. From an observational methodology perspective, the study is classified as follow-up, idiographic, and multidimensional (Anguera, Villaseñor, Mendo, & Lopéz, 2011). The data was collected throughout the competitive seasons of 2020 and 2021, which allowed a large sample to be collected (a total of 540 individual observations). Players wore GPS units (Polar®, Team Pro, Kempele, Finland) within a chest strap during every match. The chest strap was worn at the beginning of the warm-up to facilitate satellite identification and reduce missing data. After the match, the researchers collected the devices and analyzed the data using the Polar Team Pro online software. The devices were synced with the online system by positioning them into a dock station connected to a tablet (iPad 6th generation – Apple Inc. – California, USA).

A fifteen-minute threshold was set to assess how scoring a goal affected the behavior of both the players and teams. This approach is consistent with previous studies in the literature (Jones, Greig, Mawéné, Barrow, & Page, 2018; Mohr, Krustrup, Andersson, Kirkendal, & Bangsbo, 2008) that used similar thresholds for analyzing key moments in a match. Consequently, whenever a goal was scored, we divided the positional data into two time intervals, before and after the goal, within these fifteen-minute windows. If a goal was scored with less than fifteen minutes remaining until half-time or full-time, we adjusted the data to ensure a balance between the periods before and after the goal, even if the goal was scored early in the match (e.g., in the 12th minute). If a goal was scored within the final five minutes of a period, it was not included in the sample. Games without any goals were excluded as well. Ultimately, we focused exclusively on the moments before and after the first goal, as it is widely recognized that this initial goal tends to influence subsequent events in a match significantly.

To account for individual analysis, only the players who engaged in the whole fifteen-minute period were included. In case a substitution took place between these periods, the collective data was still collected, but the player was not included in the individual analysis. This procedure was required to avoid bias regarding changing the playing position of the substitute players on the reported responses.

After filtering out matches with late and early goals, our final sample consisted of 27 matches, representing 72.9% of all the available matches. The comprehensive analysis encompassed twenty-seven instances before a goal was scored, ten moments following a goal in favor of the team, and seventeen moments following a goal against the team. For individual player analysis, this study analyzed 270 instances before a goal, 100 instances after a goal in favor, and 170 instances after a goal against. We excluded one match from the sample due to poor GPS data quality, likely caused by a closed stadium environment. Player positions after the game were determined by the coaching staff, in accordance with the team's strategy.

Instruments and variables

Players' positional data responses during matches were collected using a GPS (global positioning system – Polar Team Pro) with a 10 Hz sampling rate. Athletes wore a chest strap designed by the manufacturer to carry the GPS units. This equipment's validity and reliability were tested in a previous study (Akyildiz, Yildiz, & Clemente, 2020). In addition, the reliability of GPS-based tactical variables has also been established in the literature (Praça, Abreu, et al., 2022).

The tactical behavior of players and teams was analyzed by processing the positional data provided by the GPS device, as previously adopted in the literature (Low et al., 2020; Praça, Chagas, et al., 2021), using the software MATLAB R2010a (The MathWorks Inc., Natick, MA, USA). Each player's latitude and longitude data were synchronized and converted into meters using the Universal Transverse Mercator (UTM) coordinate system and a MATLAB routine (Palacios, 2006). The corners of the field were manually obtained by the researchers in every field and were adopted as the referential system for the positional analysis. The data were smoothed using a second-order 5 Hz Butterworth low pass filter. After converting the positional data into meters, a rotation matrix was calculated for each game with the positions of the field vertices, aligning the length of the playing field along the x-axis and the width along the y-axis. Then, the rotation matrix was applied to players' positional data to align with the referential playing field (Folgado, Duarte, Fernandes, & Sampaio, 2014). The following variables were calculated: width and length, determined by the distance between the furthest players in length and the rightmost and leftmost players in width (Clemente, Bernardo Sequeiros, Correia, Silva, & Martins, 2018); length-per-width (LPW) ratio (Folgado et al., 2014); stretch index (Clemente et al., 2018); and spatial exploration index (SEI), defined as the average difference between a player's average position and his actual position at each moment of the game (Clemente et al., 2018). The LPW ratio indicates the preferential positional axis of the team, with higher values indicating a more in-depth positioning (Praça, Moreira, et al., 2021). The SEI indicates how a player explores the pitch, irrespective of the preferential axis, with higher values indicating a more exploratory behavior (Praça, Moreira, et al., 2021). The width, length, LPW ratio, and stretch index were collectively measured, while the SEI was individually analyzed.

Data analysis

The data were firstly checked for the assumptions of normality (Shapiro-Wilk's –homoscedasticity (Levene's) and sphericity (Mauchly's). Concerning the sphericity analysis, when the homoscedasticity analysis revealed p-values lower than 0.05, the Greenhouse-Geisser correction was used to adjust the degrees of freedom and reduce the type I error. One-way ANOVAs were used to compare the positional data between the three contextual contexts (before the goal, after the goal in favor, and after the goal conceded). Bonferroni's *post-hoc* tests were performed when the ANOVA indicated significant differences. The partial eta squared was calculated and classified as small effect ($0.02 < \eta^2_p < 0.13$), medium effect ($0.13 < h^2_p < 0.26$), or large effect ($\eta^2_p < 0.26$) (Pierce, Block, & Aguinis, 2004). All the analyses were conducted using the software IBM SPSS Statistics (version 19; SPSS, Inc., Chicago, IL, USA).

Results

Figure 1 shows the descriptive data regarding the collective variables. A significant effect of the context was observed in the width values ($F_{(2,53)}$=5.584, p=.006, h^2_p=0.183, medium effect).

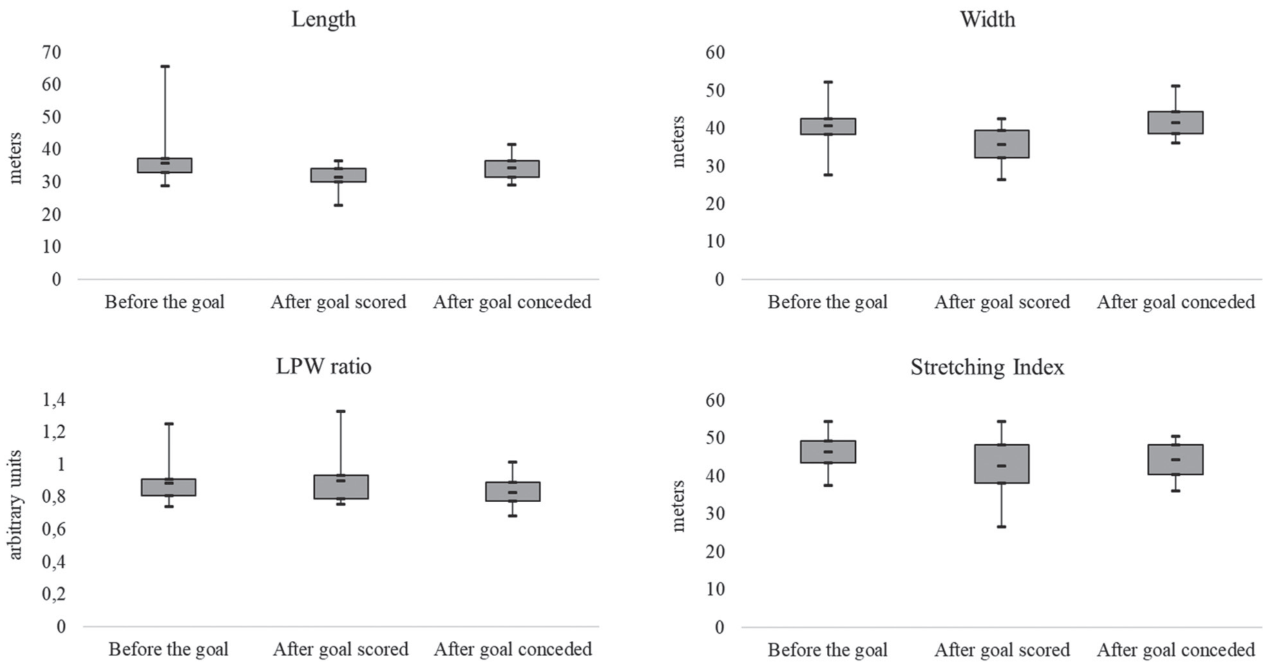


Figure 1. Boxplots of the collective variables

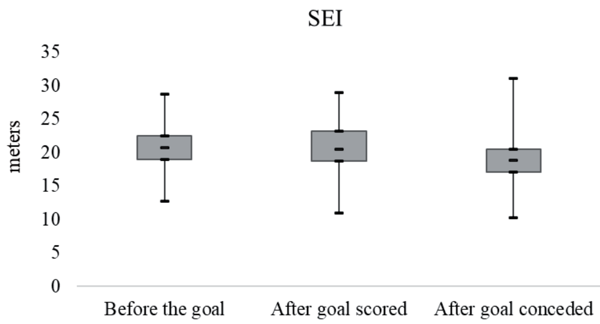


Figure 2. Boxplot for the spatial exploration index

At this point, the after-goal-in-favor moment showed lower values than the other two situations. There were no significant differences in the length ($F_{(2,53)}$=3.100, p=.054, h^2_p=0.110, small effect), and stretching index ($F_{(2,53)}$=1.806 p=.175, h^2_p=0.067, small effect). Figure 1 also shows the descriptive data related to the LPW ratio. No significant differences were reported between the contexts ($F_{(2,53)}$=1.162, p=.321, h^2_p=0.044, small effect).

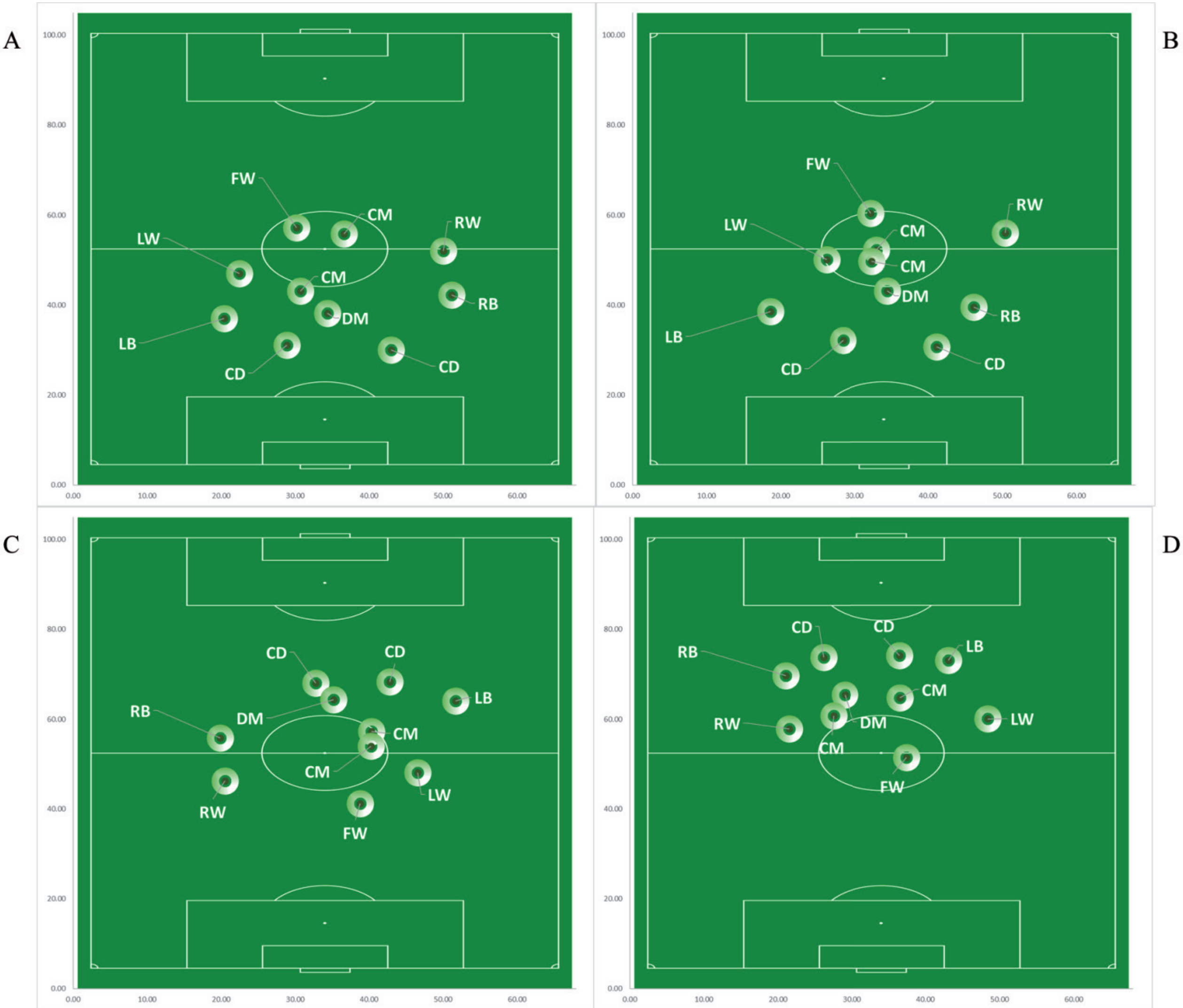
Figure 2 shows the SEI descriptive data, which indicates lower values for the after-goal-conceded condition compared with all the other contexts ($F_{(2,53)}$=21.672, p<.001, h^2_p=0.075, small effect).

Finally, Figure 3 shows the positional comparison between the moments from different matches as an example of positional changes due to a scored goal. It is possible to notice a higher proximity of the players in the midfield after the goal conceded (3B) than before the goal (3A), indicating reduced spatial exploration. Also, the reduction in the width (3D) is noticeable after scoring a goal compared to before the goal (3C).

Discussion and conclusions

The current study aimed to compare the tactical positional data of official U-20 soccer matches between three contextual situations: fifteen minutes before the first goal was scored, fifteen minutes after a goal in favor was scored, and fifteen minutes after a goal against was scored. The results indicate that a scored goal reduced the width positioning of the team. Besides, from an individual perspective, players tended to explore fewer pitch areas after their team conceded a goal.

Concerning the collective variables, a previous study indicated that final third entries were less frequent after the team scored a goal (Lago-Peñas & Gómez-López, 2014). Similarly, a 2018 FIFA World Cup study indicated that teams tended to adopt a more direct play style when winning (Praça et al., 2019), characterized by in-width positioning and a preference for long and forward passes. This result has been expanded recently in the investigation of the 2022 World Cup, in which reducing the width in the pitch's final third was assumed as a positive performance indicator for the teams (Praça, Brandão, de Oliveira Abreu, Oliveira, & de Andrade, 2023). Both results align with the current ones, which indicates a tendency to reduce width after scoring a goal. In addition, a previous study showed that, when defending, players tend to be closer to each other, reducing the possibility of the offensive team finding passing lanes (Moura et al., 2012). The strategy to protect the own goal, associated with the possibility of exploring counterattacks due to the need of the opposing team to advance the defensive lines, might explain these results. In summary, both results confirm the orig-



Note. RB: right back; CD: central defender; LB: left back; DM: defensive midfielder; CM: central midfielder; FW: forward; LW: left-wing; RW: right-wing. Changes in tactical occupation can be observed when comparing after the goal conceded (B) with before the goal (A) moments and after the goal scored (D) with before the goal scored (C) moments.

Figure 3. Example of changes in positional responses due to changes in match status

inal hypothesis that teams would adopt a more conservative tactical positioning after scoring a goal to avoid being scored.

Regarding the SEI, a previous study indicated that after scoring a goal, teams showed a higher percentage of successful passes (Redwood-Brown et al., 2019). Similarly, a higher frequency of short passes was reported for winning teams compared to drawing and losing teams during the EURO 2016 (Konefał et al., 2018). As reported in the literature, a higher difficulty in passing after conceding a goal might be explained by the current score. Specifically, we found lower values of spatial exploration after the team conceded a goal (the goal-against situation). Spatial exploration is a key to creating passing lanes and promoting unbalances in the opposing defensive system (Praça, Andrade, et al., 2021). Therefore, due to difficulties in dealing with the unfavorable score, players explored less available space, reducing their passing success.

The absence of previous studies on positional data before and after a goal scored hinders the discussion of the current study. Therefore, additional investigations are recommended at different playing levels and contexts. Also, the positional data was gathered from a single club, which requires caution when generalizing the results. Besides this caution, practical applications can be drawn. Firstly, training for moments in which the players experience conceding or scoring a goal must be addressed by coaches. This might be achieved by manipulating task constraints that elicit similar positional tactical behavior. For example, it has been shown that progression-to-the-target small-sided games led to a higher positional exploration, mainly in length, compared to regular games (Praça, Andrade, et al., 2021). Therefore, this seems an exciting task constraint to stimulate players to progress through the pitch when in possession, which seems relevant after conceding a goal. Also, floaters can be used to replicate low-positioning defensive strategies (which seems to be the case after being scored) as they were reported to stimulate ball circulation (Castellano, Silva, Usabiaga, & Barreira, 2016; Padilha, Guilherme, Serra-Olivares, Roca, & Teoldo, 2017; Praça, Clemente, de Andrade, Morales, & Greco, 2017). Besides task constraints, informational constraints can be manipulated to lead to transferrable adaptions (Chow, 2013; Shafizadeh, Davids, Correia, Wheat, & Hizan, 2016). At this point, creating situations in which players have to start the task by losing or winning by one goal might elicit the emergence of patterns similar to those required in actual match-play.

Finally, match analysts and researchers might benefit from the results of the current study. Firstly, the mere information that scoring a goal impacts positional demands should be considered when elaborating game plans and interventions on the pitch. For example, designing *a priori* alternative strategies in case an early goal is conceded or scored might be interesting to facilitate the coaching process through matches. Also, as recently postulated, the whole match positional analysis likely hinders the complete comprehension of the sports performance phenomenon (Praça, Moreira, et al., 2022). Therefore, besides the already investigated goal-scoring and game phase influence, researchers and practitioners are encouraged to open the black box of positional data and look at the detailed information instead of whole-match summaries. This will allow a deep comprehension of intrinsic match dynamics and likely increase the quality of training prescription and match planning.

The current study, besides being innovative, presents certain limitations. First, we observed all the matches of a single team. Although the number of matches and players was high, future studies with more diverse samples are recommended. Also, only linear position-based variables were adopted. Measures such as players' synchronization (Aguiar, Goncalves, Botelho, Lemmink, & Sampaio, 2015) might provide interesting insights into the within-game changes and should be explored in future studies.

In summary, it is concluded that positional tactical variables are affected by scoring or conceding a goal in official matches. Specifically, a more conservative tactical positioning, characterized by in-width concentration, will likely happen after scoring a goal. On the other hand, after conceding a goal, players tend to explore the pitch less.

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TRAINING LOAD AND PLAYERS' READINESS MONITORING METHODS USED IN VOLLEYBALL: A SYSTEMATIC REVIEW

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Review
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Abstract:

Monitoring workloads during training and competition and players' readiness seems to be key to increasing performance, reducing injury incidence and avoiding overtraining. We systematically reviewed the methods used to measure workloads and athletes' readiness in volleyball to help coaches make the best decision when selecting monitoring methods. Databases Web of Science, Scopus, SPORTDiscus and PubMed were searched from inception to the 21st of February 2022. All peer-reviewed original research in English, Spanish, Portuguese and Italian, longitudinally monitoring loads and athlete readiness in indoor volleyball team settings of any level, gender and age were included. The quality of evidence was evaluated with a modified risk of bias assessment used in previous research by Castellano et al. (2014). This study has been registered in PROSPERO ID CRD42022316313. Out of 1774 records identified, 78 were screened of which 55 full texts were added for systematic review. For internal workload, the session rating of perceived exertion (sRPE) seems to be the "golden standard" used from 2010 to 2022 across all the studies. External workload has mainly been researched through quantified jumps. Even with technological advances and the introduction of microsensors in 2017, the use of video analysis is still present nowadays. Players' readiness studies mainly used the total quality recovery scale (TQR) and wellness questionnaires in most research. New technological advances offer coaches more extensive and real-time data on external load. However, the use of the sRPE, TQR/WB, CMJ would create a monitoring system sufficient for teams at developmental stages and are of a reduced cost.

Keywords: *workload, monitoring methods, wellness, readiness, performance*

Introduction

Volleyball is a dynamic and unpredictable sport that stands out for the combination of high-intensity efforts with short periods of rest at low intensity. Among the skills that a volleyball player should possess, the following stand out: at a physical level, lower limb power, accelerations and decelerations over short distances (Sheppard & Newton, 2012), and at a technical level: setting, serving, blocking and attacking, which are highly influenced by the jumping action (Sheppard, Nolan & Newton, 2012).

Due to the high density of eccentric actions, together with the high number of impacts generated by landings and braking, an increase in fatigue and muscle damage is to be expected, which can lead to a decrease in athletic performance (Eliakim, et al., 2009; Souglis, Bogdanis, Giannopoulou, Papadopoulos & Apostolidis, 2015). That, in addition to the competitive density of the sport itself and certain contextual factors, can lead to a suboptimal recovery state (Clemente, et al., 2017; Fessi, et al., 2016).

This highlights the importance of knowing the state of our athletes and their progression towards previously established objectives. Also, that knowledge helps in the decision-making of coaches and technical staff regarding possible modifications in planning (Jeffries, et al., 2022). To this end, it seems essential to know the effects of training and competition on athletes at physiological, psychological and biomechanical levels, among others. More specifically, it is necessary to analyze training effects from the point of view of the work performed (external load) and of the response of athletes' body to the performance of this work (internal load). Coaches need to know the effect of the loads applied (acute, chronic, positive and negative) and the contextual and individual factors of each player (Jeffries, et al., 2022).

The range of load quantification methods that have been used over the years is very extensive but we can observe that certain methods stand out in scientific literature over others. Among the internal load quantification methods, the subjective perception of effort in the session (sRPE) (Foster, et al., 2001) or, at the objective level, heart rate and training impulse (TRIMP). Among the most current external load quantification methods are GPS systems, microsensors, and accelerometers (Bourdon, et al., 2017). It is also worth mentioning those tools that allow us to know the state of athletes' readiness through questionnaires (wellness or wellbeing). Although not scientifically validated (Jeffries, et al., 2020), they are widely used by sports professionals in their decision-making and can be at the same level of use as the total quality recovery scale (TQR) or the recovery-stress questionnaire for athletes (REST-Q) scales.

Despite a large number of options available, a consensus on the methods that should be used for monitoring athletes (Scott, Duthie, Thornton & Dascombe, 2016) does not yet exist and, specifically in volleyball, there is a lack of clarity on the tools that should be used to monitor loads and players' readiness status. Although some recent reviews have been able to detect the tools used in volleyball (Pisa, Zecchin, Gomes, Norberto & Puggina, 2022), they have only focused on internal loads with professional and male players, which could still generate a total lack of clarity. Therefore, this study aims to systematically review the scientific literature to know the methods and tools used in volleyball for the control of training loads, match loads and readiness status in volleyball teams with the secondary objective of helping coaches and technical staff in the decision-making process when selecting the most appropriate monitoring and readiness tools for their teams.

Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 protocol was used for this systematic review (Page, et al., 2021).

Research strategy

A systematic search of four electronic databases was conducted: PubMed, Scopus, Web of Science, and SPORTDiscus. The combination of different terms in title, abstract or keywords was made as follows: (Volleyball AND ("monitor*" OR "control" OR "record*" OR "quantif*") AND ("load*" OR "internal load*" OR "external load*" OR "training load*" OR "match load*" OR "internal training load*" OR "external training load*" OR "workload" OR "training intens*" OR "training respon*" OR "subjective" OR "objective" OR "fatigue" OR "non-functional overreaching" OR "recovery" OR "readiness" OR "wellness" OR "wellness questionnaire" OR "wellbeing" OR "well being" OR "well-being" OR "mood" OR "stress" OR "sleep") NOT "beach volleyball"). The range for years was established from the earliest available record to the 21st of February 2022. To reduce the chances of studies being left out, reference lists of included articles and relevant reviews were scanned to ensure a wider reach of our search.

Inclusion and exclusion criteria

Eligibility criteria were established using the PICO model from the PRISMA 2020 report (Page, et al., 2021):

The manuscripts selected in this systematic review followed these criteria: (1) studies based on either internal load, external load, readiness for training/matches or any combination of the three; (2) studies collecting longitudinal data of workloads and/or player's readiness in training, matches or both events; (3) articles on indoor volleyball; (4) English, Italian, Portuguese or Spanish versions of the studies; (5) original research published in a peer-reviewed journal of players enrolled in a team setting of any age, level or gender; (6) studies from the database inception to 21st of February 2022.

Exclusion criteria were established as follows: (1) studies evaluating injury prevention or reduction; (2) studies on beach volleyball; (3) manuscripts checking validity and reliability or focusing on specific drills or testing specific individual physiological demands; (4) studies with exact measurements (5) experimental studies, conference abstracts or unpublished manuscripts.

Study selection

Database search results were added to reference manager Mendeley (Elsevier, London, UK) where duplicate articles were removed. Titles and abstracts screening of remaining records was performed by the first author RV. Then, full texts were analyzed against inclusion criteria by RV and, in case of uncertainty, MPMA and AUE were consulted for discussion and reaching a final consensus.

Data collection

The first author examined and extracted information from the selected studies to be included in the systematic review into a specifically created spreadsheet. When possible, the following data were extracted from each article following the "Population, Intervention, Comparison, Outcome" (PICO) framework: (1) sample size, gender, age, playing level and country; (2) study duration, study period, study observation (only training, only matches or both); (3) instruments used (e.g. sRPE, questionnaires, video analysis), characteristics of instruments (scales, devices, thresholds); (4) study goals, study variables, main results, outcome and conclusions; (5) statistical analysis; (6) study design.

Risk-of-bias assessment

Studies were evaluated qualitatively using modified assessment criteria from Castellano, Alvarez-Pastor, and Bradley (2014) (Table 1). The main modifications were as follows: item eight was removed from the original tool as irrelevant to the current review, and answers in item 7 were converted into "YES" or "NO", so all the questions could be affirmative or negative to avoid question scores. Finally, rewording of the remaining eight items was applied to better adapt the tool to this systematic review criteria. A maximum of eight positive responses could be achieved depending on how the criteria were met. The risk-of-bias assessment was used to weigh a study's contribution to the results. Articles with a positive response of five or above were considered to carry full weight, whereas for those with four or fewer "Yes" contributions to the results were halved. RV applied the tool to each of the included studies; in the case of discrepancies, they were solved by a discussion with the remaining authors.

Data synthesis

The synthesis of data was made descriptively with the information presented in text and detailed tables. The goal of this systematic review was to observe the most used methods for monitoring workloads and players' readiness in volleyball. Since a recompilation of the results of the studies was not sought, meta-analysis was not taken into consideration. The main goal of a meta-analysis is to statistically analyze results from a relatively homogeneous group of studies, to integrate their results. The selected studies were deemed heterogeneous in variables, methods, interventions, reporting, outcome measures and study designs. Also, meta-analysis can only analyze studies with specific statistical information, therefore discarding qualitative studies.

Results

Selected studies

Initially, 1774 records were retrieved from the different databases (PubMed = 307, SPORTDiscus = 423, Web of Science = 443, Scopus = 601). A total of 677 were removed as duplicates. After screening the remaining titles and abstracts, 78 articles were selected for the full-text analysis. The rationale for rejecting full texts was as follows: language (Çelebi & Aksu, 2018; Maksimenko, Maksimenko, Zhilina & Bayeva, 2019; Sattler, 2021), not considered monitoring or athletes' readiness research (Bara Filho, de Andrade, Nogueira & Nakamura, 2013; Garcia-de-Alcaraz, Valadés & Palao, 2017; Mroczek, et al., 2014; Podstawski, Boraczynski, Nowosielska-Swadzba & Zwolinska, 2014; Zhou, 2021), not on volleyball (Hamlin, Wilkes, Elliot, Lizamore & Kathiravel, 2019), injuries and/or rehabilitation studies (Hurd, Hunter-Giordano, Axe & Snyder-Mackler, 2009; Sole, Kavanaugh & Stone, 2017; Visnes & Bahr, 2013), not following up continuously or longitudinally (Hank, Zahalka & Maly, 2015; Horta, Bara Filho, Miranda, Coimbra & Werneck, 2017; Hurd, et al., 2009; Moreira, et al., 2013; Mortatti, Pinto, Lambertucci, Hirabara & Moreira, 2018; Noce, et al., 2008; Pires & Ugrinowitsch, 2016; Pires & Ugrinowitsch, 2021; Reynoso-Sánchez, et al., 2016) and no full-text available due to journal's embargo (Gielen, Mehuys, Berckmans, Meeusen & Aerts, 2022; Ungureanu, Brustio, Boccia, Rainoldi & Lupo, 2021; Xue, 2017). After further exploration of references, two records were recouped (Freitas, Miloski, & Bara Filho, 2015; Lacerda, et al., 2015) and added to the final 55 studies included in the systematic review. (See Table 2 for reference of the included studies.) A flow chart of the process is presented in Figure 1.

Studies were published between 2010 and 2022. Out of the 55 studies included in this review, 10 studies covered the 2010-2015 period, 33 period of 2016-2020 and 12 two years 2021-2022. Regarding gender, 33 studies included only male participants, 19 female, and three both. In terms of level, 32

Table 1. Risk of bias assessment criteria

	Criteria	Answer	
1	The study is published in a peer-reviewed journal	No	Yes
2	The study is published in an indexed journal	No	Yes
3	The study objective(s) is/are clearly set out	No	Yes
4	Either the number of recordings is specified or the distribution of player/recordings used is known	No	Yes
5	The duration of player recordings (how many weeks/training sessions, how many matches, etc.)	No	Yes
6	A distinction is made according to player position, training session type and/or match	No	Yes
7	The reliability/validity of the instrument is not stated or is mentioned	No	Yes
8	The results are clearly presented	No	Yes

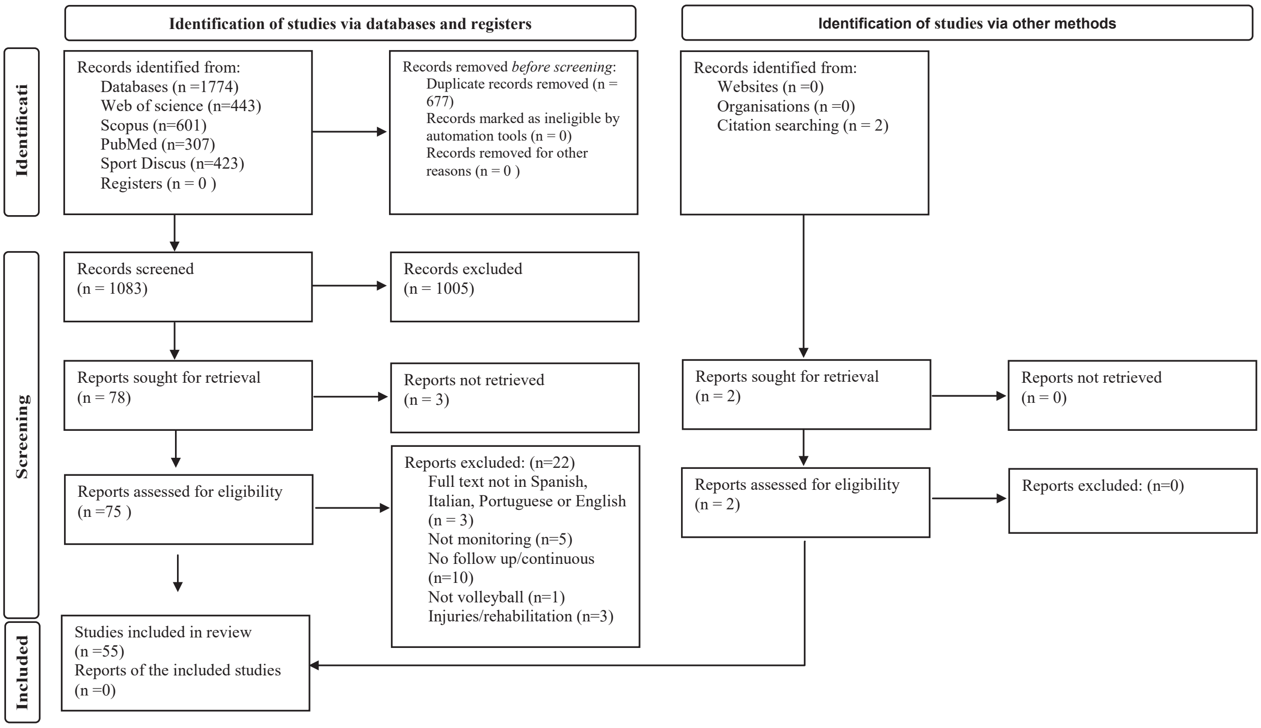

Fig. 1. Studies selection process flow chart recommended in the PRISMA, 2020. Outlining the path followed to select articles included in the systematic review

Table 2. Participants' characteristics (number, gender, level) and results of methodological quality assessment of a study

Study	Year	N	Gender	Level	Quality questions								
					Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Total
Andrade et al.	2021	15	Male	Professional Brazil	Y	Y	Y	Y	Y	Y	N	Y	7
Aoki et al.	2017	18	Male	U16 & U19	Y	Y	Y	N	N	Y	Y	Y	6
Bahr & Bahr	2014	44	Both	Junior volleyball Norway	Y	Y	Y	Y	Y	Y	N	Y	7
Brandão et al.	2018	14	Male	Professional	Y	N	Y	Y	Y	Y	Y	Y	7
Cardoso et al.	2021	9	male	Professional Brazil	Y	Y	Y	Y	Y	Y	N	Y	7
Carroll et al.	2019	11	Female	NCAA D1	Y	Y	Y	Y	Y	Y	N	Y	7
Castello et al.	2018	10	Female	NCAA D1	Y	N	Y	Y	N	N	Y	Y	5
Clemente et al.	2019	13	Male	Professional Portugal	Y	Y	Y	Y	Y	Y	Y	Y	8
Clemente et al.	2020	13	Male	Professional Portugal	Y	Y	Y	Y	Y	Y	N	Y	7
Coyne et al.	2021	63	Female	Olympic level	Y	Y	Y	Y	Y	Y	Y	Y	8
de Andrade et al.	2014	15	Male	National level Brazil	Y	Y	Y	Y	Y	Y	N	Y	7
De Leeuw et al.	2021	10	Male	Elite	Y	Y	Y	Y	Y	Y	Y	Y	8
Debien et al.	2018	15	Male	Professional Brazil	Y	Y	Y	Y	Y	Y	N	Y	7
Duarte et al.	2019	14	Male	Professional Brazil	Y	Y	Y	Y	Y	Y	N	Y	7
Duarte et al.	2019	15	Male	Professional Brazil	Y	Y	Y	Y	Y	Y	N	Y	7
Edmonds, Schmidt & Siedlik	2021	14	Female	NCAA D1	Y	Y	Y	Y	Y	Y	Y	Y	8
Freitas et al.	2014	16	Male	Professional Brazil	Y	Y	Y	Y	Y	Y	Y	Y	8
Freitas et al.	2015	7	Male	Under 16 Brazil	Y	Y	Y	Y	Y	Y	Y	Y	8
Freitas, Miloski & Bara Filho	2015	12	Male	National league	Y	Y	Y	Y	Y	Y	N	Y	7
García-de-Alcaraz et al.	2020	11	Male	Professional Spain	Y	Y	Y	Y	Y	Y	N	Y	7
Háp et al.	2011	8	Male	Professional Czech Republic	Y	Y	Y	Y	Y	Y	N	Y	7
Haraldsdottir et al.	2021	17	Female	NCAA D1	Y	Y	Y	N	Y	N	N	Y	5

Table 2. (Continued)

Study	Year	N	Gender	Level	Quality questions								
					Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Total
Hernández-Cruz et al.	2017	12	Male	Professional Mexico	Y	Y	Y	N	Y	Y	Y	Y	7
Herring & Fukuda	2022	14	Female	NCAA Div 1	Y	Y	Y	Y	Y	Y	Y	Y	8
Horta et al.	2017	15	Male	Professional Brazil	Y	Y	Y	Y	Y	Y	Y	Y	8
Horta et al.	2019	12	male	elite	Y	Y	Y	Y	Y	Y	Y	Y	8
Horta et al.	2019	12	Male	Professional Brazil	Y	Y	Y	Y	N	Y	N	Y	6
Horta et al.	2020	9	Male	Professional Brazil	Y	Y	Y	Y	Y	Y	Y	Y	8
Kraft et al.	2020	56	Female	NCAA D2	Y	Y	Y	Y	Y	Y	Y	Y	8
Kupperman et al.	2021	11	Female	NCAA Div 1	Y	Y	Y	Y	N	Y	N	Y	6
Lacerda et al.	2015	8	male	professional	Y	Y	Y	Y	Y	Y	N	Y	7
Libs et al.	2019	3	Female	NCAA D1	Y	Y	Y	Y	Y	Y	N	Y	7
Lima et al.	2019	5	Male	Professional Portugal	Y	Y	Y	Y	Y	Y	Y	Y	8
Lima et al.	2020	8	Male	Professional Portugal	Y	Y	Y	Y	Y	Y	Y	Y	8
Lima et al.	2021	10	Male	Portuguese 1st division	Y	Y	Y	Y	Y	Y	Y	Y	8
Malisoux et al.	2013	269	both	Elite juniors	Y	Y	Y	Y	Y	Y	N	Y	7
Mendes et al.	2018	13	Male	Professional Portugal	Y	Y	Y	N	Y	Y	N	Y	6
Moreira et al.	2010	20	male	Juniors	Y	Y	Y	Y	Y	Y	N	Y	7
Piatti et al.	2021	12	Male	Elite	Y	Y	Y	Y	Y	Y	Y	Y	8
Rabbani et al.	2021	13	Female	Iran national team	Y	Y	Y	Y	Y	Y	N	Y	7
Rabello et al.	2019	18	Male	Top Dutch division	Y	Y	Y	Y	Y	Y	Y	Y	8
Rodríguez-Marroyo et al.	2014	12	Female	Spanish Primera National	Y	Y	Y	N	Y	Y	N	Y	6
Roy et al.	2019	15	Female	University Canada	Y	N	Y	N	Y	N	Y	Y	5
Roy et al.	2020	15	Female	University Canada	Y	N	Y	N	Y	N	Y	Y	5
Sanders et al.	2018	1	Female	NCAA D1	Y	Y	Y	Y	Y	Y	Y	Y	8
Skazalski et al.	2018	14	Male	Professional Qatar	Y	Y	Y	Y	Y	Y	Y	Y	8
Tavares et al.	2018	13	Male	U19 Portugal	Y	Y	Y	Y	Y	Y	Y	Y	8
Taylor et al.	2019	14	Female	NCAA D1	Y	Y	Y	Y	Y	Y	N	Y	7
Taylor et al.	2022	16	female	NCAA D1	Y	Y	Y	Y	Y	Y	Y	Y	8
Timoteo et al.	2017	12	Male	Professional Brazil	Y	Y	Y	Y	Y	Y	N	Y	7
Timoteo et al.	2021	14	Male	Professional Brazil	Y	Y	Y	Y	Y	Y	N	Y	7
Ungureanu et al.	2021	10	Female	Professional Italy	Y	Y	Y	Y	Y	Y	Y	Y	8
van der Does et al.	2017	86	Both	University Netherlands	Y	Y	Y	Y	Y	Y	Y	Y	8
Vlantes & Readdy	2017	11	Female	NCAA D1	Y	Y	Y	Y	Y	Y	Y	Y	8
Wolfe et al.	2019	19	Female	NCAA D1	Y	Y	Y	Y	N	Y	N	Y	6
								Average					7,2

NCAA: National Collegiate Athletic Association
Q1-Q8: Y= yes; N= no

articles focused on the professional and elite level, 14 on the university competition level and nine on juniors and recreational players.

Quality of the studies

The quality of the included studies was considered medium-high as an average of seven positive responses ("YES") were obtained and no study received less than five. This means all studies got the same weight for the results. A more explanatory description of quality is illustrated in Table 2.

Monitoring methods

Studies showed a tendency to use a combination of different methods (36 articles). However, it is important to point out that, from the remaining 19 studies using a single metric, the majority of them were able to retrieve more than one derivative from one method (e.g., microsensors obtaining jump count, jump height, jumps per position, jump frequency), hence multiple metrics were obtained. From these articles, seven studies only used internal measures (Castello, Reed, Lund, & Mack, 2018;

de Andrade, et al., 2014; Freitas, Miloski, et al., 2015; Háp, et al., 2011; Horta, Coimbra, Miranda, Werneck, & Bara Filho, 2017; Horta, Bara Filho, Coimbra, Werneck, & Miranda, 2019; Malisoux, Frisch, Urhausen, Seil, & Theisen, 2013), eight exclusively external (Bahr & Bahr, 2014; Herring & Fukuda, 2022; Lima, Palao, Castro, & Clemente, 2019; Piatti, et al., 2021; Skazalski, Whiteley, & Bahr, 2018; Taylor, Kantor, Hockenjos, Barnes, & Dischiavi, 2019; Taylor, Barnes, Gombatto, Greenwood, & Ford, 2022; Wolfe, et al., 2019) and the remaining four investigated readiness (Carroll, Wagle, Sole, & Stone, 2019; Haraldsdottir, Sanfilippo, McKay, & Watson, 2021; Hernández-Cruz, et al., 2017; van der Does, Sanne Brink, Ardi Otter, Visscher, & Plechelmus Marie Lemmink, 2017). From studies combining measures, 22 mixed internal workload and readiness (Andrade, Fernandes, Miranda, Reis Coimbra, & Bara Filho, 2021; Cardoso, Berriel, Schons, Costa, & Kruel, 2021; Carroll, et al., 2019; Clemente, et al., 2019; de Andrade, et al., 2014; Duarte, Alves, et al., 2019; Edmonds, Schmidt, & Siedlik, 2021; Freitas, Nakamura, Miloski, Samulski, & Bara Filho, 2014; Freitas, Nakamura, et al., 2015; Herring & Fukuda, 2022; Lima, et al., 2021; Lima, et al., 2019; Malisoux, et al., 2013; Rabbani, Agha-Alinejad, Gharakhanlou, Rabbani, & Flatt, 2021; Rabello, Zwerver, Stewart, van den Akker-Scheek, & Brink, 2019; Skazalski, et al., 2018; Tavares, Simões, Matos, Smith, & Driller, 2018; Taylor et al., 2022; Timoteo, et al., 2021; Ungureanu, Lupo, Boccia, & Brustio, 2021), four internal and external loads with readiness (all 3 together) (Cardoso, et al., 2021; de Leeuw, van der Zwaard, van Baar, & Knobbe, 2022; Kupperman, Curtis, Saliba, & Hertel, 2021; Ungureanu, Lupo, et al., 2021), five internal and external loads (Libs, Boos, Shipley, Peacock, & Sanders, 2019; Lima, et al., 2021; Lima, Silva, Afonso, Castro, & Clemente, 2020; Rabello, et al., 2019; Vlantes & Readdy, 2017), three used two different internal load measures (Duarte, Coimbra, et al., 2019; Rodríguez-Marroyo, Medina, García-López, García-Tormo, & Foster, 2014; Roy, Caya, Charron, Comtois, & Sercia, 2020) and other two different external load measures (Garcia-de-Alcaraz, Ramírez-Campillo, Rivera-Rodríguez, & Romero Moraleda, 2020; Sanders, Boos, Shipley, Scheadler, & Peacock, 2018). Following a timeline, we can observe 12 studies combining methods from 2010 to 2018 and then an exponential increase between 2019 to 2021 with 23 studies in this period.

A full descriptive illustration of monitoring measures in chronological order, to observe the evolution of methods through time, is available in Table 3 and Figure 2.

Internal load

Internal load was tracked in 41 studies (74.5%) (Andrade, et al., 2021; Aoki, et al., 2017; Brandão, et al., 2019; Cardoso, et al., 2021; Castello, et al., 2018; Clemente, et al., 2019, 2020; Coyne, Coutts, Newton, & Haff, 2021; de Andrade, et al., 2014; de Leeuw, et al., 2022; Debien, et al., 2018; Duarte, Alves, et al., 2019; Duarte, Coimbra, et al., 2019; Edmonds, et al., 2021; Freitas, et al., 2014; Freitas, Miloski, et al., 2015; Freitas, Nakamura, et al., 2015; Háp, et al., 2011; Horta, Coimbra, et al., 2017; Horta, Bara Filho, Coimbra, Miranda, & Werneck, 2019; Horta, Bara Filho, Coimbra, Werneck, et al., 2019; Horta, et al., 2020; Kraft, et al., 2020; Kupperman, et al., 2021; Lacerda, et al., 2015; Libs, et al., 2019; Lima, et al., 2021; Lima, et al., 2020; Malisoux, et al., 2013; Mendes, et al., 2018; Moreira, de Freitas, Nakamura, & Aoki, 2010; Rabbani, et al., 2021; Rabello, et al., 2019; Rodríguez-Marroyo, et al., 2014; Roy, et al., 2019, 2020; Tavares, et al., 2018; Timoteo, et al., 2017, 2021; Ungureanu,

Table 3. Characteristics of study duration and methods used to monitor load in each article

Study	Monitoring method	Year
Moreira et al.	sRPE[a] / RPE[b] / sRPE derivatives + Other readiness	2010
Háp et al.	Other internal	2011
Malisoux et al.	sRPE / RPE / sRPE derivatives	2013
Bahr & Bahr	Video analysis (Jump/Swing count/load)	2014
Freitas et al.	sRPE / RPE / sRPE derivatives + other internal + CMJ[c]/SJ[d]/Rsi[e] + TQR[f] + REST-Q[g]	2014
Rodríguez-Marroyo et al.	sRPE / RPE / sRPE derivatives + HR[h]	2014
de Andrade et al.	sRPE / RPE / sRPE derivatives	2014
Lacerda et al.	sRPE / RPE / sRPE derivatives + TQR	2015
Freitas et al.	sRPE / RPE / sRPE derivatives + CMJ/SJ/Rsi + REST-Q	2015
Freitas, Miloski & Bara Filho	sRPE / RPE / sRPE derivatives	2015
Vlantes & Readdy	sRPE / RPE / sRPE derivatives + Microsensor (Jump/swing count/load) (Jump/swing count/load)	2017
Timoteo et al.	sRPE / RPE / sRPE derivatives + TQR + WB	2017

Table 3. Characteristics of study duration and method used to monitor load in each article (continuation)

Study	Monitoring method	Year
Horta et al.	sRPE / RPE / sRPE derivatives	2017
Aoki et al.	sRPE / RPE / sRPE derivatives + other readiness	2017
Hernández-Cruz et al.	HRV[i]	2017
van der Does et al.	REST-Q	2017
Sanders et al.	Microsensor (Jump/swing count/load)	2018
Skazalski et al.	Microsensor (Jump/swing count/load)	2018
Brandão et al.	sRPE / RPE / sRPE derivatives + WB + TQR	2018
Tavares et al.	sRPE / RPE / sRPE derivatives + CMJ/SJ/Rsi + WB + other readiness	2018
Mendes et al.	sRPE / RPE / sRPE derivatives + WB	2018
Debien et al.	sRPE / RPE / sRPE derivatives + TQR	2018
Castello et al.	sRPE / RPE / sRPE derivatives	2018
Rabello et al.	sRPE / RPE / sRPE derivatives + Microsensor (Jump/swing count/load) + Video analysis (Jump/Swing count/load)	2019
Libs et al.	HR + Microsensor (Jump/swing count/load)	2019
Lima et al.	Microsensor (Jump/swing count/load)	2019
Wolfe et al.	Video analysis (Jump/Swing count/load) + Other external	2019
Taylor et al.	Video analysis (Jump/Swing count/load)	2019
Duarte et al.	sRPE / RPE / sRPE derivatives + TQR + WB	2019
Clemente et al.	sRPE / RPE / sRPE derivatives + WB	2019
Roy et al.	sRPE / RPE / sRPE derivatives + WB	2019
Duarte et al.	sRPE / RPE / sRPE derivatives + HR	2019
Horta et al.	sRPE / RPE / sRPE derivatives + other internal + REST-Q	2019
Horta et al.	sRPE / RPE / sRPE derivatives	2019
Carroll et al.	CMJ/SJ/Rsi	2019
Lima et al.	sRPE / RPE / sRPE derivatives + Microsensor (Jump/swing count/load)	2020
García-de-Alcaraz et al.	Video analysis (Jump/Swing count/load)	2020
Clemente et al.	sRPE / RPE / sRPE derivatives + WB	2020
Horta et al.	sRPE / RPE / sRPE derivatives + TQR + other readiness	2020
Kraft et al.	sRPE / RPE / sRPE derivatives + HR + other readiness	2020
Roy et al.	sRPE / RPE / sRPE derivatives + Other Internal	2020
Lima et al.	sRPE / RPE / sRPE derivatives + Microsensor (Jump/swing count/load) + Video analysis (Jump/Swing count/load) + other external	2021
Kupperman et al.	sRPE / RPE / sRPE derivatives + Microsensor (Jump/swing count/load) + WB + other external	2021
Piatti et al.	Microsensor (Jump/swing count/load)	2021
Ungureanu et al.,	sRPE / RPE / sRPE derivatives + HR + WB + Video analysis (Jump/Swing count/load)	2021
Rabbani et al.	sRPE / RPE / sRPE derivatives + HR + HRV + CMJ/SJ/Rsi + WB	2021
De Leeuw et al.	sRPE / RPE / sRPE derivatives + other external + WB	2021
Edmonds, Schmidt & Siedlik	HR + HRV + WB	2021
Haraldsdottir et al.	WB	2021
Andrade et al.	sRPE / RPE / sRPE derivatives + TQR	2021
Timoteo et al.	sRPE / RPE / sRPE derivatives + TQR	2021
Cardoso et al.,	sRPE / RPE / sRPE derivatives + HRV + TQR + other readiness	2021
Coyne et al.	sRPE / RPE / sRPE derivatives + other readiness	2021
Herring & Fukuda	Microsensor (Jump/swing count/load)	2022
Taylor et al.	Microsensor (Jump/swing count/load)	2022

Note. [a]sRPE: session rating of perceived effort; [b]RPE: rating of perceived effort; [c]CMJ: counter movement jump; [d]SJ: squat jum [e]RSi: reactive strength index; [f]TQR: total quality recovery scale; [g]REST-Q: recovery-stress questionnaire; [h]HR: heart rate; [i]HRV: heart rate variability.

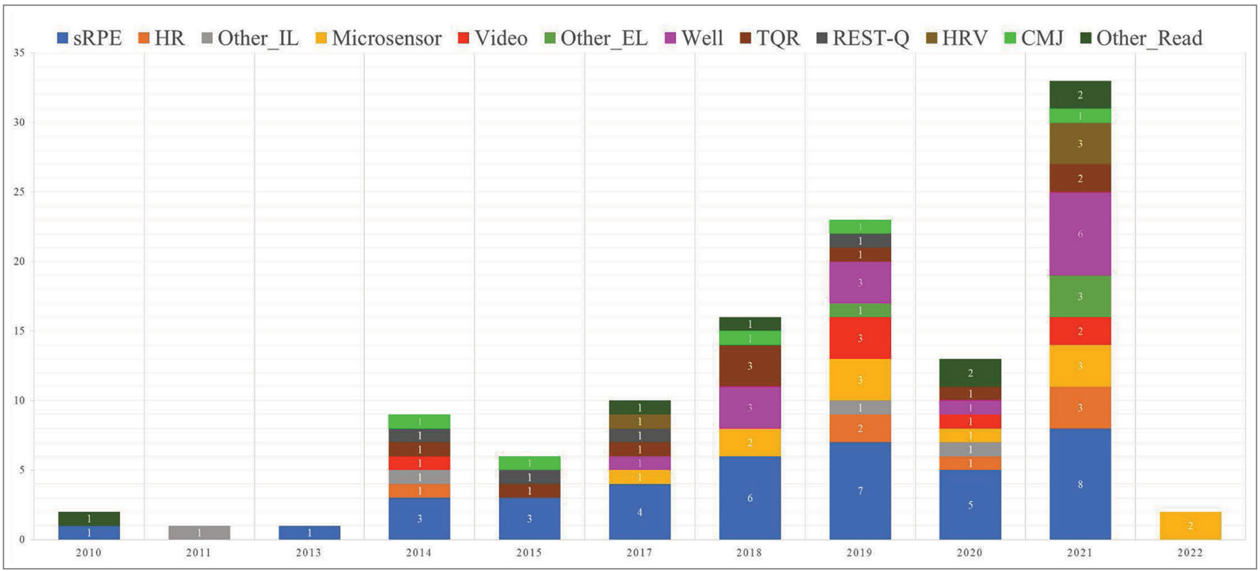

Fig. 2. Chronological evolution of the use of different measurement instruments found in the selected studies included in this systematic review.

Lupo, et al., 2021; Vlantes & Readdy, 2017), 38 of them (92.7%) operated with the sRPE/RPE as a measure for internal training and competition loads (Andrade, et al., 2021; Aoki, et al., 2017; Brandão, et al., 2019; Cardoso, et al., 2021; Castello, et al., 2018; Clemente, et al., 2019, 2020; Coyne, et al., 2021; de Andrade, et al., 2014; de Leeuw, et al., 2022; Debien, et al., 2018; Duarte, Coimbra, et al., 2019; Duarte, Alves, et al., 2019; Freitas, et al., 2014; Freitas, Miloski, et al., 2015; Freitas, Nakamura, et al., 2015; Horta, Coimbra, et al., 2017; Horta, Bara Filho, Coimbra, Miranda, et al., 2019; Horta, Bara Filho, Coimbra, Werneck, et al., 2019; Horta, et al., 2020; Kraft, et al., 2020; Kupperman, et al., 2021; Lacerda, et al., 2015; Lima, et al., 2021; Lima et al., 2020; Malisoux, et al., 2013; Mendes, et al., 2018; Moreira, et al., 2010; Rabbani, et al., 2021; Rabello, et al., 2019; Rodríguez-Marroyo, et al., 2014; Roy, et al., 2019, 2020; Tavares, et al., 2018; Timoteo, et al., 2017, 2021; Ungureanu, Lupo, et al., 2021; Vlantes & Readdy, 2017). All the studies recording sRPE applied the Category Ratio Scale 10 (CR-10) (Foster, et al., 2001). Multiple studies (18) took advantage of the versatility of the sRPE using derivatives. The sum of daily workloads into a weekly internal training load (WITL), monotony, strain and acute to chronic workload ratio (ACWR) were the most employed (Andrade, et al., 2021; Clemente, et al., 2019, 2020; de Leeuw, et al., 2022; Debien, et al., 2018; Duarte, Coimbra, et al., 2019; Freitas, et al., 2014; Freitas, Miloski, et al., 2015; Horta, Coimbra, et al., 2017; Horta, Bara Filho, Coimbra, Werneck, et al., 2019; Horta, Bara Filho, Coimbra, Miranda, et al., 2019; Horta, et al., 2020; Lacerda, et al., 2015; Malisoux, et al., 2013; Rabbani, et al., 2021; Rodríguez-Marroyo, et al., 2014; Timoteo, et al., 2021). Objective internal measures were less used among the selected studies, with seven records using HR (Duarte, Alves, et al., 2019; Edmonds, et al., 2021; Kraft, et al., 2020; Libs, et al., 2019; Rabbani, et al., 2021; Rodríguez-Marroyo, et al., 2014; Ungureanu, Lupo, et al., 2021) and three other methods such as: saliva and blood markers (Háp, et al., 2011; Horta, Bara Filho, Coimbra, Miranda, et al., 2019; Roy, et al., 2020). See Table 3.

Regarding the usage of the above measures through the years, the sRPE, RPE and its derivatives have been used evenly from 2010 to 2022. However, HR was mostly used (in six out of seven studies) from 2019 to 2021. See Figure 2.

Athletes' readiness

Analyses of data collected from wellness or well-being questionnaires (WB) (Hooper & Mackinnon, 1995; McLean, Coutts, Kelly, McGuigan, & Cormack, 2010) were the most observed methods for the assessment of athletes' readiness in 14 studies (Brandão, et al., 2019; Clemente, et al., 2019, 2020; de Leeuw, et al., 2022; Duarte, Coimbra, et al., 2019; Edmonds, et al., 2021; Haraldsdottir, et al., 2021; Kupperman, et al., 2021; Mendes, et al., 2018; Rabbani, et al., 2021; Roy, et al., 2019; Tavares, et al., 2018; Timoteo, et al., 2017; Ungureanu, Lupo, et al., 2021), followed by the Total Quality Recovery Scale (TQR), used in 10 studies (Andrade, et al., 2021; Brandão, et al., 2019; Cardoso, et al., 2021; Debien, et al., 2018; Duarte, Coimbra, et al., 2019; Freitas, et al., 2014; Horta, et al., 2020; Lacerda, et al., 2015; Timoteo, et al., 2017, 2021). Other questionnaires such as the Recovery Stress Questionnaire for Sports (REST-Q-sports) were used in four studies (Freitas, et al., 2014; Freitas, Nakamura, et al., 2015; Horta, Bara Filho, Coimbra, Miranda, et al., 2019; van der Does, et al., 2017), the Profile of Mood States (POMS) in two studies (Aoki, et al., 2017; Horta, et al., 2020) and lastly the Daily Analyses of Life Demands of Athletes (DALDA) in one study (Moreira, et al., 2010). Other different scales were also found in our review, with one study each: the Rating of Perceived Recovery (RPR) (Kraft, et al., 2020), the Visual Analogue Scale (VAS) for mental fatigue (Coyne, et al., 2021) and the Perceived Recovery State (PRS) (Cardoso, et al., 2021). Objective measures were also collected, via heart rate variability (HRV) (Cardoso, et al., 2021; Edmonds, et al., 2021; Hernández-Cruz, et al., 2017; Rabbani, et al., 2021) and countermovement jump (CMJ) (Carroll, et al., 2019; Freitas, et al., 2014; Freitas, Nakamura, et al., 2015; Rabbani, et al., 2021; Tavares, et al., 2018) in four and five studies, respectively. See Table 3.

If a chronological order of use in studies is implemented for readiness measures, the first method detected is DALDA in a 2010 study, followed by the REST-Q sport, TQR and CMJ from 2014 to 2019-2021 and lastly WB and HRV from 2017 to 2021. See Figure 2.

External load

The most studied variables to monitor external workload were vertical displacement variables, specifically, jump count and/or jump load. In 12 studies microsensors were used to measure workload (predominantly VERT Classic and Catapult Sports' Optimeye 5S) (Herring & Fukuda, 2022; Kupperman, et al., 2021; Libs, et al., 2019; Lima, et al., 2019, 2021, Lima et al., 2020; Piatti, et al., 2021; Rabello, et al., 2019; Sanders, et al., 2018; Skazalski, et al., 2018; Taylor, et al., 2022; Vlantes & Readdy, 2017), but also: jump height, establishing height thresholds, detect jump type and measure jump intensity from the devices' integrated gyroscope, magnetometer and tri-axial accelerometer. Other metrics such as player load, vertical accelerations, high impacts, high impacts % and explosive efforts could also be obtained from their software.

Video analysis was also used in seven studies (Bahr & Bahr, 2014; Garcia-de-Alcaraz, et al., 2020; Lima, et al., 2021; Rabello, et al., 2019; Taylor, et al., 2019; Ungureanu, Lupo, et al., 2021; Wolfe, et al., 2019) for jump count/load, the detection of the type of jumps/landings, jumps by position, the calculation of distances covered by players, technical actions quantification (sets, spikes, serves, blocks, digs, receptions, defences). Other methods were also observed for external workload monitoring, including swing count (Wolfe, et al., 2019), Changes of direction, accelerations, decelerations, and high-intensity efforts (Kupperman, et al., 2021), data volley variables (defences, receptions, digs…) (Lima, et al., 2021) and sets, repetitions and loads in the gym and/or court sessions (de Leeuw, et al., 2022). See Table 3.

Finally, if we look at the evolution of external methods through the years, the first method to be observed in volleyball studies on external load was the video analysis of jump load in 2014. In 2017 microsensors started to appear, and from there, all the methods are evenly used from 2019 onwards. See Figure 2.

Discussion and conclusions

This systematic review seeks to address the lack of consensus on the selection of training and competition load monitoring tools (Fox, Stanton, Sargent, Wintour, & Scanlan, 2018) as well as on the methods for assessing the readiness of volleyball players. The findings of this review are intended to provide valuable information for sports professionals to facilitate their informed decision making about their training plans (Jeffries, et al., 2022). To achieve this purpose, we presented the most commonly used methods found in scientific literature and their trend of use over time with the intention to provide an updated record of tools that can be employed by any volleyball team.

In this review, three clearly defined types of tools have been identified and described in the current literature (Jeffries, et al., 2022). These tools are divided into those that monitor internal loads, those that focus on external loads, and those used to assess players' readiness.

In volleyball, it is common to use multiple monitoring tools (Clemente, et al., 2019; Mendes, et al., 2018). To make more accurate planning decisions, it is recommended to combine tools that measure internal loads, external loads, and players' readiness (Burgess, 2017; De Beéck, et al., 2019; Fox, et al., 2018; S. Ryan, Kempton, & Coutts, 2021; Saw, Main, & Gastin, 2016).

The sRPE is a popular tool for internal monitoring due to its simplicity and ability to provide detailed information. For assessing players' readiness, the TQR scale, wellness questionnaires and the CMJ are prominent options. For external loads, it is important to measure a variety of actions, ideally using microsensors in all three axes of motion.

Objective measurement, through technological advances in devices, shows a steady increase in the literature since 2017. Especially in technology focused on quantifying workloads during on-court sessions. Among the most prominent contributions of technology is the ability to provide real-time information (Garcia-de-Alcaraz, et al., 2020; Lima, et al., 2021; Ungureanu, Lupo, et al., 2021) and to quantify load in all spatial axes (Kupperman, et al., 2021).

However, subjective methods through questionnaires have continued to be used. In some cases, there is an explicit confrontation between the objective and subjective sources. For example, although objective methods exist to measure internal load, such as heart rate for the calculation of TRIMP (Bara Filho, et al., 2013; Duarte, Alves, et al., 2019; González, et al., 2005; Kraft, et al., 2020; Libs, et al., 2019; Rodríguez-Marroyo, et al., 2014), a preference for the use of sRPE has been observed.

Technological advances in the search for greater objectivity in measurement are intrinsic to scientific research and sports training.

The use of subjective tools such as the sRPE and wellness questionnaires has also been found to affect self-awareness and, in addition, to promote the development of self-regulation (Vavassori, Moreno, & Ureña, 2023).

Therefore, from a perspective based on subjective insight, there is a phenomenological approach (Sousa, 2014; Vavassori, et al., 2023; Zahavi, 2020) that could provide value in terms of self-regulation.

Studies on self-regulation have highlighted its relevance in sports development, performance and readiness (Balk & Englert, 2020; Harrison, et al., 2022). In addition, its importance has been evidenced in issues related to well-being (Crawford, Tripp, Gierc, & Scott, 2021), which includes the aspects assessed in the wellness questionnaires analyzed in this review. However, it was not that there was hidden knowledge about the value of self-regulation. Rather, there was a comfort and/or accessibility that was not refuted by the technology. Hence the importance of giving added value to qualitative instruments.

Possibly, the extensive use of sRPE in volleyball (Pisa, et al., 2022) may also be due to the existing relationship between various tools regardless of their objective or subjective nature.

Although the focus in volleyball has been on quantifying jumps for years, it is relevant to note that less than 50% of a players' total load on the court comes from jumps, as significant load occurs during horizontal movements (Vlantes & Readdy, 2017). Volleyball is characterized by a series of small movements, accelerations, decelerations and changes of direction that generate high stress on players, and thanks to technological advances, these can be detected through microsensors (Kupperman, et al., 2021).

On the other hand, obtaining real-time information allows for faster and highly individualized training decisions. Individualization in the monitoring and planning of sessions is crucial, since, for example, the volume and intensity of jumps vary significantly depending on the role of each player (Skazalski, et al., 2018; Vlantes & Readdy, 2017). This highlights the importance of establishing player-specific load thresholds (Brito, Hertzog & Nassis, 2016; Kellmann, et al., 2018). However, we should not underestimate another potential benefit of the immediate feedback offered by some technologies, such as the stimulation of self-motivation. Motivation theories distinguish between mastery-focused motivation and ego-focused motivation (Ryan & Deci, 2000). In the case of volleyball student-athletes using objective tools, it has been observed that their motivation is mainly focused on outperforming their teammates (Vavassori, et al., 2023). Therefore, we should not dismiss the motivational contributions they can derive from technology and objective methods.

Although these two perspectives (objective and subjective) are interconnected, as information from the objective world can influence human consciousness and decisions, technological advances transform the subjective into objective information for information systems (Xu, et al., 2023). Therefore, although the relationship between these two dimensions is complex, the information is simultaneously subjective and objective (Bates, 2006).

In summary, using the sRPE (and its derivatives), TQR/WB, CMJ would create a monitoring system sufficient for teams in developmental stages and at a reduced cost. Furthermore, it is worth insisting on taking advantage of the added value in terms of self-regulation and motivation provided by the use of qualitative instruments. However, the combination of these tools with microsensors would result in a complete and real-time monitoring system for decision-making of the volleyball team staff.

Limitations and strengths

Because of the reduced number of researches regarding monitoring in the sport of volleyball compared to other team sports (soccer, rugby, Australian football), limitations may arise in the current review. Many studies identified used a limited number of participants. Although volleyball teams usually have 12-14 players, and collecting data from more than one team might not be feasible, small sample conclusions should be taken with caution. Also, there might have been some selection bias as in team sports, the composition of the teams is already set and players are not selected randomly. Another possible selection bias could have arisen from the decision to use only one author for the initial selection of studies. Even though PRISMA allows the use of a single author for this stage, some studies might have been wrongly included or excluded during the process.

Comparison between studies is not advised, as findings in studies with different statistical analyses may be complicated. Meta-analysis is suggested in the future to solve this issue. However, to minimize this effect, article quality was assessed to reduce bias and include higher standard research in the results. We may have incurred in risk of bias by not executing a dual and independent screening. Nevertheless, we are confident that the conclusions of this review have not been affected by these methodological limitations.

Important to notice that, due to different playing levels, ages and genders, training control methods should be adapted to each team, situation, level, goals, and limiting factors.

Despite these constraints, we consider the information provided in this systematic review may contribute to increasing team performance, avoiding non-functional overreaching and hence, mitigating injury occurrence by selecting monitoring methods supported by science and used by professionals in elite and development teams in volleyball. It may also help coaches in selecting the best available method to monitor the load and readiness of their teams.

Future directions

In this review, two studies quantified load on 3 axes measuring vertical and horizontal displacement with wearable microsensors, concluding vertical displacement loads cover less than half of the training and match loads. Consequently, horizontal movements create greater workloads (Kupperman, et al., 2021; Vlantes & Readdy, 2017). Thus, more research is needed as most studies in the past focused solely on jumps.

All sessions of a training week (gym, individual training, rehab) either in the preseason or competitive period should be investigated further. Since the current research has limited the information to on-court sessions only, we feel an immense quantity of load is discarded. Furthermore, some studies did not include match loads in the weekly load calculation, creating false load information. Keep in mind that match load usually is the highest load of the week (Brito, et al., 2016; Fessi & Moalla, 2018; Murphy, Duffield, Kellett, & Reid, 2016).

From our search, there was no study observing training loads and readiness distribution during the off-season. Collecting information during this period might assist in anticipating the planning of workloads for the preseason, normally the period with the highest volume of the year (Andrade, et al., 2021; Aoki, et al., 2017; Horta, Bara Filho, Coimbra, Miranda, et al., 2019). By doing so, coaches should be able to avoid excessive spikes in load by having access to workload data from the transition period. Studies in the future may shed light on what methods are used to monitor players when are away from team settings.

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CASE STUDY: CARBOHYDRATE SUPPLEMENTATION IMPROVES ULTRA-ENDURANCE PERFORMANCE IN A KETO-ADAPTED INDIVIDUAL

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Case study
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Abstract:

Ketogenic dietary interventions cause a dramatic increase in fat oxidation, with a growing body of research indicating prolonged ketogenic diets do not impair exercise performance. However, there is neither strong evidence in support of such a strategy. Over prolonged endurance events, the need for carbohydrates becomes increasingly important to prevent glycogen depletion and hypoglycaemia. A case study methodology was used to examine the response of an ultra-endurance runner with experience of events ranging from 60 to 161km (age: 37; stature: 184cm; mass: 80.2±0.8kg; $\dot{V}O_{2max}$ 56.5ml/kg/min; mean training volume 37km/week) to three identical 67km field tests following an 8-week ketogenic dietary intervention. Supplementation protocols comprised an acute carbohydrate feeding on the day of competition (74g carbohydrate [0.92g/kg pre-race], 310g [3.85g/kg] during race), in addition to a condition comprising an acute feed as well as a two day of carbohydrate feed (200g carbohydrate [2.5g/kg] in two day feed, 44g carbohydrate [0.54g/kg pre-race], 310g [3.85g/kg] during race), prior to the event and these were compared to baseline event where no carbohydrate was consumed, within race feeding restricted to low carbohydrate options. Compared to baseline (05:58:47 [hours:minutes:seconds]), the 67km time trial improved in both carbohydrate feeding conditions, with greater performance improvements after acute consumption compared to the two-day feed (05:36:59 vs. 05:42:01). Rate of fat oxidation during 0-15km and 40-45km of the acute condition time trial decreased compared to baseline (0.95±0.32g/min, 0.42±0.24g/min vs. 1.20±0.34g/min, 0.89±0.02g/min), and was greatest during the two-day feed condition (1.52±0.30g/min, 1.37±0.34g/min). Carbohydrate feeding impacted substrate metabolism and improved time to complete ultra marathon performance in a ketogenic athlete emphasising the importance of carbohydrates as a fuel for exercise performance. More research is required to determine the efficacy of this strategy within ketogenic athletic populations, as well as investigating optimal ketogenic dietary practices and carbohydrate supplementation protocols.

Keywords: *fat oxidation, RER, carbohydrate feeding, carbohydrate oxidation*

Introduction

Ketogenic diets are becoming an increasingly popular fuelling regime for recreational and elite athletes (Zinn, Wood, Williden, Chatterton, & Maunder, 2017). Despite a marked increase in the contribution of fat oxidation to substrate utilisation during endurance exercise in chronically keto-adapted athletes, there is little evidence to suggest this improves exercise performance. To date the research has shown mixed results, with most studies noting no change in performance (Helge, Wulff, & Kiens, 1998; McSwiney, et al., 2018; Phinney, Bistrian, Evans, Gervino, & Blackburn, 1983; Prins, et al., 2023; Prins, et al., 2019; Zajac, et al., 2014) and in some cases, performance impairments (Burke, et al., 2017; Helge, Richter, & Kiens, 1996). Performance impairments are likely a result of the ergolytic properties associated with prolonged carbohydrate restriction, for example, decreased glycogenolysis and a reduction in the active form of pyruvate dehydrogenase (PDHa) (Stellingwerff, et al., 2006), further to this, reductions in training capacity have been shown during the adaptation to a ketogenic diet (Heatherly, et al., 2018; McKay, et al., 2023), causing a training effect that may confound short-term studies (Lindseth, 2017). There is clear evidence that acute carbohydrate ingestion improves endurance performance, with particular benefits in prolonged (~60 minute) exercise (Stellingwerff & Cox, 2014). It is therefore plausible to suggest acute carbohydrate consumption will enhance the performance of keto-adapted athletes, especially during ultra-marathon events. This may be in part due to the ability of exogenous glucose to maintain blood glucose levels, with original studies that form the basis of our understanding of the importance of muscle glycogen concentrations also showing hypoglycaemia at the termination of exercise, in addition to low muscle glycogen concentrations (Noakes, 2022) with this review emphasising the importance of the maintenance of blood glucose through the homeostatic mechanisms of liver glycogen being a driver of the metabolic response to prolonged exercise.

However, the ability of the keto-adapted athlete to absorb and utilise carbohydrates is likely to be sub-optimal, with animal research showing that reducing carbohydrate intake decreases the SGLT1 protein content of the intestine leading to reduced carbohydrate absorption and oxidation during exercise (Dyer, et al., 2009; Higashida, et al., 2019; Jeukendrup, 2017; Shirazi-Beechey, et al., 1991). This is supported by human studies showing increased daily carbohydrate consumption increases exogenous glucose (Cox, et al., 2010). It is also unknown how different carbohydrate re-introduction strategies impact oxidation rates and, ultimately, exercise performance.

A synergistic outcome that combines high rates of carbohydrate oxidation with the retention of an enhanced capacity for fat oxidation provides a means of preventing glycogen depletion and hypoglycaemia, which would otherwise limit the performance in keto-adapted individuals in prolonged endurance performance (Cox, et al., 2010), as well as influencing performance through central nervous system-based mechanisms (Maunder, Kilding, & Plews, 2018; Stellingwerff & Cox, 2014). Whilst there is a growing body of research examining the impact of ketogenic diets on endurance performance, little work has been conducted in the context of ultra-endurance performance, despite the increased importance of fat oxidation in longer exercise formats (Frandsen, Vest, Larsen, Dela, & Helge, 2017) making it a more promising area of research in the context of ketogenic diets.

Research has shown the inevitability of ketosis in multi-stage ultra-marathon races regardless of high carbohydrate feeding (Cooper, et al., 2023), suggesting that keto-adaptation may be advantageous in individuals performing over this distance. However, at present, few studies have addressed the impact of carbohydrate feeding following prolonged exposure to a ketogenic diet. Previous case study-based research has found carbohydrates to improve some aspects of performance following keto-adaptation (Webster, Swart, Noakes, & Smith, 2018), with single-case research used as a means to rigorously study participants on an individual basis, with this being a valuable methodology to study unique populations (Barker, Mellalieu, McCarthy, Jones, & Moran, 2013) such as ultra-endurance athletes on a prolonged ketogenic diet. Therefore, the aim of this case study was to determine metabolic effects and performance outcomes of acute carbohydrate feeding strategies in a keto-adapted (defined as <5% calories from carbohydrates) sub-elite ultra-endurance athlete.

Methods

A trained male ultra-endurance runner (age: 37; stature: 184cm; mass: 80.2±0.8kg; $\dot{V}O_{2max}$ 56.5ml/kg/min) was recruited to take part in this study. The participant has been competing in ultra-endurance events ranging between 60-161km for six years. The athlete followed his habitual training routine throughout the testing period, with an average of 39km per week during baseline, 33km per week during the acute carbohydrate phase, and 40km per week during the two-day carbohydrate feeding phase.

Informed consent was obtained, in addition to blood sampling consent. Ethical approval was granted by the University Ethics Board and all procedures and conduct met with the Declaration of Helsinki.

The study used a single case, ABC design. This design involved a baseline (condition A), followed by an acute carbohydrate feeding (condition B) and a two-day carbohydrate feeding (condition C).

The participant had been following a ketogenic diet for eight weeks prior to the first exercise test and tracked all food consumed for the entirety of the testing period using a mobile food logging application (MyFitnesspal, Inc) that uses a food composition database that is sourced by the App and users of the App (Tosi, et al., 2021), weighing food prior to inputting serving size. As well as this, urine ketones were monitored daily for the first fourteen days to check ketogenic status (Mission urinanalysis, San Diego, CA), with ketones achieved by day four. Food database tracking suggested 100% compliance, in addition to the urine ketone data, that showed ketosis in every test from day 4. Following the first 14 days of intervention, urine ketones were monitored every second day. The participant monitored his general diet, ensuring he adhered to a ketogenic diet; defined as <5% of total calories from carbohydrate. Body composition was evaluated to determine changes throughout the study using multi-frequency bioelectrical impedance analysis (Tanita Europe B.V. Amsterdam, Netherlands).

Body mass remained stable throughout the intervention when measured before each condition of testing, prior to interventions (mean body mass 80.2±0.8kg). Testing spanned over a 9-week period, which involved the participant completing a 67km ultra-marathon time trial (TT) under the three separate conditions. The first TT was performed in a fully ketogenic state, with no carbohydrate feeding before or during the time trail. The second TT entailed acute (on the day of the trial) carbo-

Table 1. Foods consumed on race day -2, race day -1 and on race day

Condition	**Baseline**	**Acute**	**2 Day Feed**
Race Day -2	Breakfast Egg, whole, cooked, fried, 2 large	Breakfast Sausage, 2 links Egg, fried, 2 large	Lunch Hand Cooked Sea Salt & Balsamic Vinegar Crisps (40g), 40 g
	Sausage - Sausage, 2 links		
	Lunch Cathedral City - Mature Cheese 50g, 60 g	Lunch Hamburger & Salad, 2 Plate	Roast Chicken & salad sandwich, 1 pack
	Peperami Hot - Meat Stick 22.5g, 45 g	Dinner	Dinner
	Dinner Extra Virgin Olive Oil 3 tablespoon (15g	Pork & Herb Chipolatas Seasoned With Rosemary & Thyme, 4 chipolatas	Chocolate Truffles, 2 chocolate
	Mature Cheese 50g, 30 g	Pimento Stuffed Olives With Manchego, 75 g	50% Milk Chocolate Slab, 17 g
	Roast Chicken Breast Fillet, 100 g	Mature Cheese 50g, 40 g	Butter, 3 tbls
	Passata, 99 g	Butter, 3 tbls	Wholemeal Rustic Roll, 1 roll
	Cougette, 30 g	Free Range Eggs (Medium), 232 g egg	Egg, whole, cooked, fried, 3 large
	Garlic, raw, 1 clove	Snacks	Bacon, 3 pieces
	Onion, Small Cooked	Salted Peanuts, 40 gram	Snacks
	Snacks		Mature Cheese 50g, 60 g
	Salted Peanuts 40 gram		Salted Peanuts, 40 gram
	Almond Milk – Unsweetened		Strawberries, 1 cup (144g)
	Seeds, flaxseed, 1 tbsp, whole		Fruit - Cherries - Dark Sweet No Sugar Added, 30 g
	Acai and blueberries, 15 g		Sea Salt & Balsamic Vinegar crisps, 33 g
	Coconut Oil, 1 tbsp		
Race Day -1	Breakfast	Breakfast	Breakfast
	Egg, fried, 2 large	Sausage - Sausage, 2 links	Rasins,
	Sausage - Sausage, 2 links	Egg, whole, cooked, fried, 2 large	Unsweetened Yoghurt, 80 g
	Dinner	Dinner Cypriot Halloumi Cheese, 100 g	Porridge - Oats, 90 g
	Almond Milk - Unsweetened flaxseed, 1 tbsp, whole	Lettuce, 1 cup shredded	Dinner
	Acai and blueberries, 15 g	Pimento Stuffed Olives With Manchego, 75 g	Vanilla Dairy Ice Cream
	Coconut Oil, 1 tbsp	Cucumbers, 20 g	Fresh - Strawberries, 1 cup (144g)
	Mature Cheese 50g, 40 g	Mayonnaise, 2 Tbsp (13g)	Butter, 2 tbls
	Seed Crackers, 20 g	Haimisha Cucumbers, 10 g	Baked Jacket, 100 g
	Butter, 3 tbls	Extra Virgin Olive Oil 3 tablespoon (15g)	Baked Jacket, 100 g
	Unsmoked Bacon, 200 gram	Tuna Chunks In Brine, 100 g	Mayonnaise, 50 g
	Snacks	Snacks	Extra Virgin Olive Oil 4 tablespoon (15g)
	Salted Peanuts, 40 gram	Mature Cheese 50g, 30 g	Mixed Leaf Salad, 84 g
		Salted Peanuts Original, 40 gram	Masala Chicken Breasts, 1 Pack
			Snacks Cheese Oatcakes, 6 biscuit
			Belgian Dark Chocolate Rice Thins, 2 Thin
Pre Race Meal	Coconut oil Flaxseed Almond milk Acai Blueberries	Chocolate Twist	Danish Bear Claw
During Race	Cheddar Cheese Salted Peanuts	Jaffa Cake Melon Crisps Tailwind Endurance Coca Cola	Jaffa Cake Melon Crisps Tailwind Endurance Coca Cola

Table 2. Food intake before and during ultra-endurance event

Condition	Baseline	Acute	2 Day Feed
2 Days Pre Race (Mean of 2 days ± SD)	**Calories (Kcal)** 2087 ± 511 **Carbohydrate (g)** 15 ± 5 **Fat (g)** 159 ± 44 **Protein (g)** 153 ± 87	**Calories (Kcal)** 2391 ± 331 **Carbohydrate (g)** 14 ± 0 **Fat (g)** 191 ± 12 **Protein (g)** 139 ± 48	**Calories (Kcal)** 2445 ± 130 **Carbohydrate (g)** 200 ± 82 **Fat (g)** 152 ± 2 **Protein (g)** 90 ± 12
Pre Race Meal	**Calories (Kcal)** 263 **Carbohydrate (g)** 3 **Fat (g)** 23 **Protein (g)** 20	**Calories (Kcal)** 548 **Carbohydrate (g)** 74 **Fat (g)** 22 **Protein (g)** 12	**Calories (Kcal)** 339 **Carbohydrate (g)** 44 **Fat (g)** 16 **Protein (g)** 5
During Race	**Calories (Kcal)** 371 **Carbohydrate (g)** 2 **Fat (g)** 30 **Protein (g)** 20	**Calories (Kcal)** 1398 **Carbohydrate (g)** 310 **Fat (g)** 14 **Protein (g)** 5	**Calories (Kcal)** 1398 **Carbohydrate (g)** 310 **Fat (g)** 14 **Protein (g)** 5
Total Food Consumption On Race Day	**Calories (Kcal)** 644 **Carbohydrate (g)** 5 **Fat (g)** 53 **Protein (g)** 40	**Calories (Kcal)** 1946 **Carbohydrate (g)** 384 **Fat (g)** 36 **Protein (g)** 17	**Calories (Kcal)** 1737 **Carbohydrate (g)** 354 **Fat (g)** 30 **Protein (g)** 10

hydrate consumption. This comprised a carbohydrate meal pre-TT, carbohydrate feeding during the TT and a post-TT carbohydrate meal. The final TT comprised a carbohydrate feed period beginning two days prior to the TT, as well as during it. Calories were controlled in the two days prior to the TT, and in-race nutrition strategies were identical in the two carbohydrate conditions.

Mean calorie intake throughout the testing period was 2150±511 kcal/day (range 210-2946 kcal/day). Mean daily macronutrient intake was: 15±5g (3% of total calories) carbohydrates, 175±44g fat (73% total calories), and 121±35g protein (23% total calories), with exact foods consumed around exercise testing outlined in Table 1, with the caloric and macronutrient breakdown of these foods detailed in Table 2, below.

The TT's were conducted using an identical route that the participant was familiar with, having run it previously. The route was a 12km trail that was completed in laps. Weather conditions were also similar across trials, with temperatures of 11°C, 11°C, and 15°C across the three tests respectively (Weather Underground, 2017) and all under dry conditions. Testing spanned over a 60-day period, in which three phases of testing were conducted. The acute phase was conducted 37 days following the end of the baseline phase, and the two-day phase began 13 days after the end of the acute phase.

Throughout the TT, heart rate (bpm) and distance (km) were measured continuously as well as time to completion using a running watch (Garmin Fenix 3, Garmin, Olath, Kanses). Oxygen kinetics and substrate oxidation were measured for the beginning 15km and for a 5km section between 40-45km using a Cosmed K5 (Cosmed Ltd, Via dei Piani di Monte, Sarello, PO Box 3, Pavonna di Albano, Rome, 00040 Italy). The unit was calibrated prior to each section, with the Cosmed K5 being put on the participant during a pre-scheduled food and drink station section.

Blood glucose (mmol) and lactate (mmol) were measured immediately prior, at 15km and then at subsequent 12km intervals throughout the TT, with the final measure immediately following the end of the TT. These were measured using finger-prick samples with the Biosen C-Line Sport (EKF diagnostic Sales GmbH, Ebendorfer Chaussee 3, Technologiepark Ostfalen, Germany).

Blood samples and the application of Cosmed K5 was performed simultaneously at feeding points to minimise the impact on time to completion, with all blood sampling completed prior to the participant finished consuming his relevant nutrition. Fat and carbohydrate oxidation were calculated using stochiometric equations outlined by Peronnet and Massicotte (1991).

Statistics

Data were analysed through visual analysis, with the data presented in tables and figures. Percentage change was used to determine changes in performance and physiological markers where appropriate.

Results

In the two days prior to ultra-endurance run, daily calorie intake at baseline was 2087±511 kcal/day comprising 15 ± 5g carbohydrate, 159±44g fat and 153±87g protein. During the acute condition, it was 2391±331 kcal/day, with 14±0g carbohydrate, 191±12g fat and 139±48g protein, and during the two-day load condition, it was 2445±130 kcal/day, with 200±82g carbohydrate, 152±2g fat and 90±12g protein.

On the morning of the ultra-endurance run, 263 kcal were consumed during the baseline condition, comprising 3g carbohydrate, 23g fat and 20g protein. In the acute condition, a meal comprising 548kcal, with 74g carbohydrate, 22g fat and 12g protein was consumed. In the two-day load condition, a 339 kcal meal was consumed with 44g carbohydrate, 16g fat and 5g protein. Body mass remained stable throughout the intervention when measured before each condition of testing, prior to the interventions (mean body mass 80.2±0.8kg).

67km TT (time trial) results

Time to completion (hours:minutes:seconds) was 6.1% faster during the acute condition (05:36:59) than baseline (05:58:47), with the two-day feed time (05:42:01) being 4.5% faster than baseline and 1.8% slower than under the acute condition.

Oxygen consumption and substrate oxidation, measured for the first 15km and a 5km section during the time trials, are shown alongside accompanying split times in Table 3.

Mean heart rate throughout the entirety of the TT was 148±8 bpm at baseline, 147±10 bpm during the acute condition, and 148±10 bpm in the two-day feed condition.

Lactate and glucose measures taken across the testing period are shown in Figures 1 and 2, below.

Discussion and conclusions

The main finding of this study revealed that a keto-adapted athlete's TT improved in both carbohydrate feeding conditions compared to baseline, with greater performance improvements evident after the acute consumption compared to the two-day feed (05:36:59 vs. 05:42:01). These findings, whilst only in the format of a case study, indicate that

Table 3. Pace and physiological markers during the first 15km and the 40-45km section of the TT across the three conditions

	First 15 km			Mid 5km section		
	Baseline	**Acute**	**2 Day Feed**	**Baseline**	**Acute**	**2 Day Feed**
Split time (Hours:minutes:seconds)	01:13:50	01:09:09	01:10:51	00:28:11	00:25:04	00:25:07
Oxygen Consumption (ml/kg/min)	42.3±6.6	46.7±4.0	47.1±4.9	35.3±3.1	37.7±2.6	45.4±4.4
RER	0.79±0.05	0.85±0.05	0.76±0.04	0.81±0.04	0.92±0.05	0.78±0.05
Carbohydrate Oxidation (g/min)	1.2±0.8	2.4 ± 1.0	1.02±0.7	1.37±0.57	2.95±0.66	1.24±0.85
Fat Oxidation (g/min)	1.2±0.3	0.95±0.3	1.52±0.3	0.89±0.02	0.42±0.24	1.37±0.34
Heart rate (bpm)	148±11	155±9	153±5	148±11	155±9	156±5

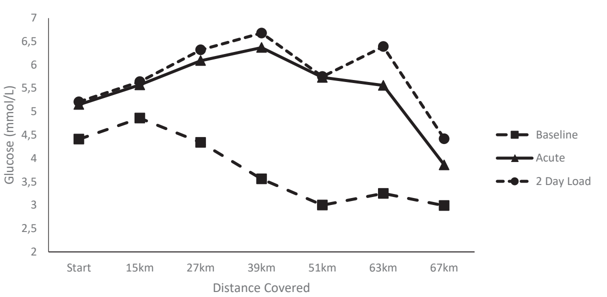

Figure 1. Glucose measurements throughout the duration of the time trial.

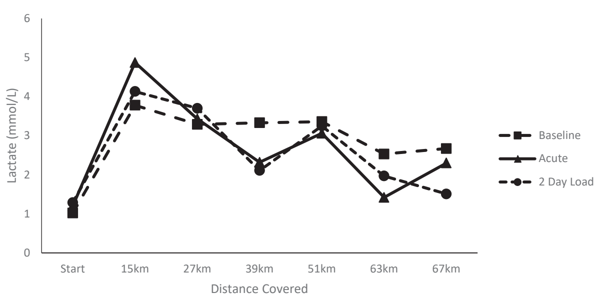

Figure 2. Lactate measurements throughout the duration of the time trial.

carbohydrates are ergogenic in keto-adapted individuals as they are in non-keto adapted individuals (Stellingwerff & Cox, 2014), despite poor glucose uptake following carbohydrate restriction (Shirazi-Beechey, et al., 1991; Stellingwerff & Cox, 2014), which may result in reduced efficacy of carbohydrate in this population. Performance improvements in longer duration activity are predominantly attributed to maintenance of glycogen stores and blood glucose, shown in Figure 2, that leads to augmented carbohydrate oxidation by the muscle (Stellingwerff & Cox, 2014; Stellingwerff, et al., 2006). This improved blood glucose maintenance prevents hypoglycaemia, which is thought to impair cognitive state (Warren & Frier, 2005) and perceived mental state (Glace, Murphy, & McHugh, 2002). This maintenance of blood glucose represents a key rationale explaining performance improvements, with hypoglycaemia occurring as a result of low hepatic glycogen content. Noakes (2022) outlined a scenario in which hypoglycaemia may in fact play a role in the homeostatic regulation of exercise, with hypoglycaemia being prevented through to ensure brain damage does not occur. This led Noakes to suggest that in endurance sports, increasing liver glycogen stores could maintain blood glucose and delay hypoglycaemia (Noakes, 2022), with the author also highlighting the fact that hypoglycaemia occurs earlier and to a greater extend on a low-carbohydrate diet, giving further rationale to this argument.

This also allows for greater uptake of glucose to skeletal muscle, alongside the reduced need for extreme rates of carbohydrate ingestion through fat adaptation. This is important in reducing the chance of gastro-intestinal (GI) distress (Stellingwerff & Cox, 2014). With up to 60-96% of ultra-marathon runners experiencing GI distress (Costa, et al., 2017), a 'live and train keto, compete carb' nutrition strategy may be a novel alternative to reduce the possibility of in race GI distress in some individuals. This method of fuelling may be a method of increasing fat metabolism and improving metabolic flexibility (Prins, et al., 2023). In addition, this study showed greater carbohydrate oxidation during the acute carbohydrate phase, which is a counter to the previous argument above. Thus, future work must explore the role of carbohydrate supplementation and changes in substrate oxidation in a larger cohort of keto-adapted individuals.

Table 3 shows fat oxidation was substantially lower during the acute condition compared to the ketogenic and two-day feeding conditions, especially compared to previously studied trained athletes (Volek, et al., 2016). In spite of this, rates of fat oxidation still exceeded those observed in non-keto adapted individuals (Venables, Achten, & Jeukendrup, 2005) and matched rates observed by well-trained keto-adapted athletes in the two-day feed condition despite carbohydrate ingestion. The two-day feeding condition showed elevated rates of fat oxidation at the beginning (1.52±0.30g/min) and in the middle section (1.24±0.85g/min) compared to both other conditions. This was despite increased oxygen consumption in the two-day load condition, demonstrating the ability to oxidise fat at an intensity (83% $\dot{V}O_{2max}$ during first 15km) that would typically be predominantly carbohydrate dependant (Romijn, et al., 1993), this is consistent with recent findings showing the crossover point is shifted for fat-adapted athletes (Noakes, Prins, Volek, D'Agostino, & Koutnik, 2023). A further key finding from the TT was the participant's ability to maintain a higher rate of oxygen consumption, and in accordance, to maintain a greater speed during carbohydrate supplementation conditions. Heart rate data further supports the ability to maintain higher intensities following carbohydrate ingestion, with a greater heart rate during the carbohydrate fed trials. Whilst lactate levels were not greatly different, they were observed to be greater throughout the second half of the TT during the ketogenic phase. This is unexpected, since through reductions in glycolysis, ketogenic interventions have previously shown reductions in exercising lactate (Zajac, et al., 2014). This may be a result of improved lactate clearance following a ketogenic intervention in all phases, as has been alluded to following four-week ketogenic interventions (Zajac, et al., 2014) in synergy with an increased rate of glycogen synthesis noted in this study. It is noted that the planned increase in pre-race muscle glycogen, presumably achieved by increased carbohydrate intake (~3 g/kg BM/d) in the two days prior to the third TT, did not appear to provide any benefit to performance above that achieved by the planned increase in exogenous CHO availability achieved through the intake of CHO (~4 g/kg) during the TT, although both strategies were associated with a faster TT than the chronic keto-adaptation alone. However, these findings are particular to an individual athlete and the circumstances of this case study, therefore a need this to be investigated in a larger cohort to determine optimal feeding strategies in keto-adapted individuals. It is also important to note that fat oxidation was greater during the two day feeding condition notwithstanding carbohydrate supplementation, supporting the previous research showing that fat oxidation can remain elevated after a period of keto-adaptation despite singular acute carbohydrate ingestion (Carey, et al., 2001; Lambert, et al., 2001). It is clear that fat oxidation was maintained at high rates and this enhanced ability to oxidise fat is particularly beneficial during ultra-endurance exercise (Frandsen, et al., 2017), thus a ketogenic dietary intervention may be useful for athletes looking to spare muscle glycogen over ultra-endurance activities. Future research should look to study this detail in more controlled settings to determine the level of the reduction in fat oxidation following carbohydrate supplementation.

We argue that interventions aimed at promoting the oxidation of endogenous fat stores are critical to the success of ultra-endurance. The evidence of this research revealed a keto-adapted athlete not only increased his fat oxidation as expected, but this persisted even after carbohydrate feeding, which is indicative of the adaptive physiological changes associated with the ketogenic diet working in synergy with acute carbohydrate feeding to monopolise metabolism pathways that can improve ultra-endurance performance. Therefore, this study provides evidence for the notion of training with low carbohydrate availability and competing with high carbohydrate availability to enhance exercise performance in keto-adapted athletes. Principally, the evidence outlined highlights the notion that this is predominantly due to the prevention of hypoglycaemia, suggesting that ketogenic athletes can benefit from carbohydrate ingestion in prolonged exercise in order to maintain normoglycaemia.

A limitation of this study is the lack of direct ketone measurement through venous or capillary blood, and more invasive measurement techniques such as muscle biopsies, and tracers to determine exogenous glucose oxidation would have allowed for further comparisons between differing carbohydrate conditions. Further to this, the reduced calorie intake during the baseline run may be a factor in performance reduction. Whilst calories were matched during both carbohydrate trials, considerably fewer calories were consumed throughout the ketogenic trial (Table 2). This is due to the participant struggling to tolerate high fat foods throughout the baseline run, limiting total calorie intake, which is an important consideration for ultra-endurance athletes. The use of a non-laboratory-based study is also a limitation, as the outside environment may confound results; however, this applied approach adds to the study's ecological validity and offers an insight into the impact of dietary manipulation in an applied setting. A further limitation is the use of a commercial app to monitor food intake which may limit the validity of food intake data since nutrition apps may cause incorrect estimations due to their food composition databased (Tosi, et al., 2021). It is important to note the differences in total calories consumed during the TT. In the ketogenic phase, the athlete consumed ~1,500 calories fewer than in both carbohydrate feeding phases, which may have impacted the time trial result.

Future research should seek to understand changes in physiology and performance following a 'live and train keto, compete carb' nutrition strategy in order to better understand optimal ways to fuel performance in ketogenic individuals. This will not only benefit individuals on ketogenic diets but better inform future research comparing ketogenic diets to standard diets, in which pre-exercise nutrition often differs between groups, with individuals on a ketogenic intervention not receiving pre-exercise carbohydrate, which may skew findings towards non-ketogenic dietary practises.

The aim of this single-case study was to assess the impact of a dietary intervention on a particular athlete from a cohort in which finding a homogenous group is challenging using a method in which practitioners may wish to replicate to optimise fuelling in keto-adapted athletes. The findings of this investigation clearly demonstrates that carbohydrate feeding enhanced time to completion in an ultramarathon in a keto-adapted individual. The synergy for oxidising carbohydrates whilst maintaining relatively high rates of fat oxidation following carbohydrate feeding is of significance to endurance athletes looking to enhance exercise performance in modalities that are impaired by limited glycogen stores. Researchers should look to study carbohydrate supplementation in larger cohorts of ketogenic athletes in order to determine the optimal use of carbohydrate in the keto-adapted athlete and better inform future ketogenic intervention studies.

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The authors declare that the results of the study are presented clearly, honestly and without falsification, fabrication or inappropriate data manipulation.

Competing interests

The authors declare that they have no competing interests.

THE EFFECTS OF CORE TRAINING ON ENDURANCE IN DIFFERENT TRUNK MOVEMENTS: A SYSTEMATIC REVIEW AND META-ANALYSIS

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Review
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Abstract:

Core muscle endurance involves the trunk muscles' capability to maintain a particular position for as much time as possible. It is essential to know how specific training aimed at this area affects endurance of different trunk movements performance and to what extent. The objective was to assess the effects of trunk training on different core muscle endurance measurements in flexion, extension, and right and left lateral flexion. A literature search was performed using different databases. The studies included: (a) cohorts of healthy people or subjects with chronic low back pain; (b) a core training intervention; (c) pre-post intervention parameters of interest; (d) a minimum of four out of 10 on the PEDro scale, and (e) randomised controlled trials. A random-effects model for meta-analyses was used. Fifteen studies were selected for the systematic review and 11 for the meta-analysis, comprising 1,213 participants. Compared to the control condition, core training induced a moderate effect on trunk flexion endurance (ES = 0.67), right-lateral trunk flexion endurance (ES = 0.77), left-lateral trunk flexion endurance (ES = 0.94), and a small effect on trunk extension endurance (ES = 0.49). To back up the results presented in this study, more research into the effects of trunk training on core muscle endurance is needed to confirm these results significantly. Core training improves core muscle endurance in four trunk movements. Core training is more effective in participants with pre-intervention poor results.

Keywords: *muscle strength, resistance training, athletic performance, exercise therapy, motor activity, physical fitness*

Introduction

The trunk zone is particularly interesting for researchers and coaches in physical activity, performance, and health (Hibbs, Thompson, French, Wrigley, & Spears 2008; Hodges, 2003). The main muscles that comprise this zone are *transversus abdominis*, internal oblique, external oblique, *rectus abdominis* and *multifidus* (Majewski-Schrage, Evans, & Ragan, 2014). The term core has been adopted by fitness centres; however, it is usually not well employed or its meaning remains unclear. The term refers to the function and capability of the central body. The main functions of the core provide force generation, generate proximal stability for distal mobility, and generate interactive movements (Kibler, Press, & Sciascia, 2006). This system is essentially designed to develop, absorb and/or transmit forces needed for human movement (Cook, 2010). Experts define core stability as "the ability to achieve and sustain control of the trunk region at rest and during precise movement" (Majewski-Schrage, et al., 2014). In this sense, core muscle endurance is understood as the trunk muscles' capability to keep a position for as much time as possible, maintaining force over time (McGill, Childs, & Liebenson, 1999). Additionally, high levels of core muscle endurance may significantly benefit musculoskeletal health (Sibson, et al., 2021).

Over the years, core exercises have been commonly prescribed for the treatment of unspecific lower back pain (LBP), or to improve athlete's performance, despite the lack of scientific evidence of solid quality about these benefits in athletes (Stuber, Bruno, Sajko, & Hayden, 2014). In adults with chronic LBP, core-based exercises seem to be one of the most effective methods to reduce pain and disability (Fernández-Rodríguez, et al., 2022). Besides, this type of training turns out to be more effective than general exercise in reducing LBP (Wang, et al., 2012). In athletes, poor core muscle endurance is likely associated with nonspecific LBP (Abdelraouf & Abdel-Aziem, 2016), but, in contrast, it is not clear that core training reduces LBP in this population (Nadler, et al., 2002). However, the core muscle endurance in trunk extension and flexion movements seems to be inversely correlated with non-specific LBP (Abdelraouf & Abdel-Aziem, 2016). Thus, it seems sensible to train these movements in this type of patients.

To put relevance of the core in context, deep core musculature is activated earlier than the anterior deltoid during arm movements (Allison & Morris, 2008) and, probably, this earlier activation is untrainable (Vasseljen, Unsgaard-Tøndel, Westad, & Mork, 2012). These results show that a strong and stable point could be necessary for the correct transfer of forces and, consequently, sports performance. In the sports performance context, a specific core training programme improves performance, increasing throwing velocity in female handball players, supporting the theory of a stable point (Saeterbakken, van den Tillar, & Seiler, 2011). Good core muscle endurance influences the ability of the subject to run intermittently, exert maximum force and power, push-up, sit and lift. In addition, individuals with higher core endurance have better quality of movement (Santos, Behm, Barbado, DeSantana, & Silva-Grigoletto, 2019). A strong and stable core provides a necessary foundation for the performance of various athletic activities, and core training seems more relevant in sports in which the core plays an important role (Reed, Ford, Myer, & Hewett, 2012).

Fitness programmes focused on the core use body weight exercises or exercises on unstable surfaces without clear justification about (Granacher, et al., 2014). Trunk training protocols usually use exercises and training variables similar to those used in core muscle endurance assessments (Hung, Chung, Yu, Lai, & Sun, 2019). For example, the front-prone plank is a common exercise used until exhaustion among athletes to assess core muscle endurance. In contrast, some sports tasks usually require trunk flexion of maximal voluntary contraction (MVC) to transfer energy from legs to arms, such as long-distance passes in rugby or a throw-in in soccer. This type of situation could be hard to replicate during usual gym core training. Thus, core endurance training could be effective in enhancing core muscle endurance but not meet the needs of the most demanding motor tasks. However, trunk training seems to be effective in improving stability (Barrio, Ramirez-Campillo, Alcaraz-Serrano, & Hernandez-García, 2022; Hsu, Oda, Shirahata, Watanabe, & Sasaki, 2018), and it could cover the demands of the specific sport. Moreover, core training promotes lumbar movement adjustments and alters the movement patterns during running (Ogaya, et al., 2021).

The most popular methods to assess core muscle endurance are field-based tests, probably due to their accessibility, easy usage and portability (Friedrich, Brakke, Akuthota, & Sullivan, 2017; Juan-Recio, López-Plaza, Barbado Murillo, García-Vaquero, & Vera-García, 2018). Different tests have been used to determine core muscle endurance, like isometric trunk flexion, isometric trunk extension and right and left side bridges (McGill, et al., 1999). In the literature, a unique test with strong reliability to assess trunk extension endurance was Biering-Sorensen isometric trunk extension (Martínez-Romero, et al., 2020). This test focused on four main movements of the trunk: flexion, extension, right flexion, and left flexion and how the trunk training may affect the capability of the trunk to maintain the position to resist over time.

Although trunk training seems effective in improving core muscle endurance (Sandrey & Mitzel, 2013), according to the pyramid-based evidence paradigm, no greater knowledge has been generated regarding trunk training and its effects on the trained population. Thus, no previous systematic review with meta-analysis (SRMA) was conducted regarding trunk training effects on core muscle endurance. In addition, the most sensible movements to train were not reported: flexion, extension and lateral flexions.

Since (i) no specific SRMA has explored the effects of trunk endurance training, (ii) the increased scientific awareness of the relevance of core training has been evidenced in the last decade (with more than 70% of all studies published in this period), and (iii) the needs to clear the relevance of core training on different trunk movements endurance, this research study aimed to conduct an SRMA to assess the effects of trunk training on different core muscle endurance measurements: flexion, extension, right and left lateral flexions. Thus, this study hypothesised that trunk training would improve all core muscle endurance measurements, especially in the most trained movements of various sports.

Methods

This systematic review was carried out according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement protocol (Moher, et al., 2009). A literature search was conducted in three of the most relevant electronic databases: PubMed, Web of Science and Scopus. The following keywords, combined with Boolean operators (AND, OR), were used: "core strength", "core muscle endurance", "core stability", and "core engagement". An example of a PubMed search is ("randomized controlled trial" [Publication Type]) OR "controlled clinical trial" [Publication Type]) AND "core" [Title/Abstract]) AND "strength" [Title/Abstract]) OR "endurance" [Title/Abstract] OR [Title/Abstract] "stability" OR [Title/Abstract] "engagement". No exclusion criteria based on the year of publication were applied. One investigator received automatically generated emails for updates regarding the search terms used. These updates were received daily (if available), and studies were eligible for inclusion until the initiation of the manuscript preparation.

Inclusion and exclusion criteria

The following inclusion criteria were applied: (a) trunk training used in intervention periods of at least two weeks of duration, defined as "exercises focusing on stimulation of one or more of the next muscles: *transversus abdominis*, internal oblique, external oblique, *rectus abdominis* and *multifidus*" (Majewski-Schrage, et al., 2014), (b) cohorts of healthy subjects or with chronic low back pain, (c) a minimum of 4 of 10 in PEDro scale, which ensures at least "moderate" quality of the study, (d) measurements of core muscle endurance that were selected based on a logically defensible rationale, and (e) randomized controlled trials with a control group. The exclusion criteria were: (a) cross-sectional, a review, or a training-related study not focused on the dynamic postural stability, (b) retrospective studies, prospective studies, studies in which trunk training was mixed with other types of training, studies for which only the abstract was available, case reports, studies with ambiguous study protocols, non-human investigations, special communications, repeated-bout effect interventions, letters to the editor, invited commentaries, errata, overtraining studies, and detraining studies (included if training period was before detraining period) and (c) non-English language studies.

Study quality assessment

The Physiotherapy Evidence Database (PEDro) (de Morton, 2009) scale was used to assess the methodological quality of the included articles. The PEDro scale is based on 11 items selected by "expert consensus". The first one requires answere "yes" or "no", and the rest ratings 0 or 1. These items show a scale where the highest value is 10 (low risk of bias) and the lowest 0 (high risk of bias). The study quality assessment was interpreted using the following 10-point scale: poor quality (≤3 points), moderate quality (4–5 points), and high quality (6–10 points) (Table 1).

Study selection

Two investigators (EDB and AGA) reviewed the studies and decided whether inclusion was appropriate. Any discrepancies were resolved via consensus with the third author (RHG). Figure 1 shows the search strategy and study selection. Out of 628 records screened, 545 were discarded due to not meeting the inclusion criteria selected by reading only the title and abstract. Out of 83 studies selected for the full text read, 68 were discarded for different reasons like not written in English, did not assess core muscle endurance, not using a control group, mixed training protocols, or high risk of bias. Four studies were removed from the systematic review (SR) to meta-analysis (MA) due to the absence of specific data or due to confusing data.

Characteristics of the studies included

For the current SRMA, the core muscle endurance measurements were selected based on a logically defensible rationale. Extracted data included the following information: type of control, type of randomisation, number of participants per group, type of test, unit of measurement for each test and the measurement of each test (flexor, extensor, right or left lateral flexor). In addition, the participants' age (years), sex, and fitness level were collected. Regarding training characteristics, the frequency of training (days per week), the duration of training (weeks), the types of exercises, with or without equipment and the sets and repetitions for each exercise were also registered.

Data extraction

The main information (authors, year, control and experimental sample, intervention duration, training frequency, total sessions, duration of each training session, type of exercises, equipment, sets, repetitions, tests, measurements and main effects) were extracted from the included studies. Two investigators verified a suitable process and discussed each item. The articles were examined and verified along with all the preliminary information collected and divided into columns in an Excel table. This way, the guideline to improved searching in PubMed (Schardt, Adams, Owens, Keitz, & Fontelo, 2007) was followed to search methodological gaps as experts recommended. To perform meta-analysis, mean pre-post, standard deviations (SD) and the number of subjects (n) were extracted and arranged on another Excel page. The Image J software (National Institutes of Health, Bethesda, MD, USA) program was used to capture the information from studies that only included results on graphics.

Data analysis

For the analysis and interpretation of results, meta-analyses were conducted if at least three studies provided baseline and follow-up data for the same parameter (García-Hermoso, Ramírez-Campillo, & Izquierdo, 2019). Further analysis was carried out (flexion, extension, left and right-lateral trunk endurance). Means and standard deviations (SD) for each measure of trunk endurance pre-post-intervention were converted to Hedges's g effect size (ES). The continuous random-effects model for meta-analysis was used because it allocates a proportional weight to trials based on the size of their individual standard errors (Deeks, et al., 2019) and facilitates analysis while accounting for heterogeneity across studies (Kontopantelis, Springate, & Reeves, 2013). In this sense, the likelihood approach with random effects was used to better account for the inaccuracy in the estimate of between-study variance (Hardy & Thompson, 1996). The ESs were presented alongside 95% confidence intervals (CIs). The calculated ES were interpreted using the conventions outlined for standardized mean difference: <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 (Hopkins, Marshall, Batterham, & Hanin, 2009). All analyses were conducted using the Comprehensive Meta-Analysis program (version 2; Biostat, Englewood, NJ, USA).

To gauge the degree of heterogeneity amongst the studies included, the percentage of total variation across the studies due to heterogeneity (Cochran's Q-statistic) (Higgins, Thompson, Deeks, & Altman, 2003) was used to calculate the I2 statistic. This value represents the proportion of effects due to heterogeneity compared to the chance (Moher, et al., 2009). Low, moderate and high levels of heterogeneity correspond to I2 values of <25%, 25-75%, and >75%, respectively (Higgins, et al., 2003; Higgins & Thompson, 2002). However, these thresholds are considered tentative (Higgins, et al., 2003). The Chi-square test assesses whether any observed differences in results are compatible with chance alone. A low p-value or a large Chi-square statistic relative to its degree of freedom provides evidence of heterogeneity of intervention effects beyond those attributed to chance (Deeks, et al., 2019). The risk of bias across the studies was assessed using the extended Egger's test (Egger, Smith, Schneider, & Minder, 1997).

Results

Figure 1 provides a graphical schematisation of the study selection process carried out by PRISMA. Through database searching, 790 records were initially identified. Finally, 15 studies were considered in SR (Aggarwal, Kumar, & Kumar, 2010; Chuter, de Jonge, Thompson, & Callister, 2015; Jamison, et al., 2012; Junker & Stöggl, 2019; Kuhn, Weberruß, & Horstmann, 2019; Lust, Sandrey, Bulger, & Wilder, 2009; Mayer, et al., 2014, 2016; Ozmen & Aydogmus, 2016; Sannicandro, 2017; Shamsi, Sarrafzadeh, Jamshidi, Zarabi, & Pourahmadi, 2016; Stanton, Reaburn, & Humphries, 2004a; Toprak Çelenay, & Özer Kaya, 2017; Tse, McManus, & Masters, 2005; Weston, Coleman, & Spears, 2013) and 11 for the MA (Aggarwal, et al., 2010; Jamison, et al., 2012; Junker & Stöggl, 2019; Lust, et al., 2009; Mayer, et al., 2014, 2016; Ozmen & Aydogmus, 2016; Sannicandro, 2017; Shamsi, et al., 2016; Stanton, et al., 2004a; Tse, et al., 2005), involving 16 experimental groups and 15 control groups, with 649 (412 males, 120 females, and 117 non-defined sex) and 564 (355 males, 121 females, and 88 non-defined sex) subjects, respectively.

Quality of the studies

Supplementary file 1 shows the quality of the studies included in the SRMA. Eleven out of 15 studies were considered high-quality (Aggarwal, et al., 2010; Chuter, et al., 2015; Jamison, et al., 2012; Junker & Stöggl, 2019; Kuhn, et al., 2019; Mayer, et al., 2014, 2016; Sannicandro, 2017; Shamsi, et al., 2016; Toprak Çelenay & Özer Kaya, 2017; Weston, et al., 2013) and four as moderate quality (Lust, et al., 2009; Ozmen & Aydogmus, 2016; Stanton, et al., 2004a; Tse, et al., 2005). The mode was 6 points, and the mean was 6.2 points for SRMA and 6.1 for 11 articles included in MA.

Characteristics of the studies included

Table 1 synthesises studies in the SRMA (Aggarwal, et al., 2010; Chuter, et al., 2015; Jamison, et al., 2012; Junker & Stöggl, 2019; Kuhn, et al., 2019; Lust, et al., 2009; Mayer et, al., 2014, 2016; Ozmen & Aydogmus, 2016; Sannicandro, 2017; Shamsi, et al., 2016; Stanton, et al., 2004a; Toprak Çelenay & Özer Kaya, 2017; Tse, et al., 2005; Weston, et al., 2013). Nine articles included male and female athletes (Aggarwal, et al., 2010; Chuter, et al., 2015; Junker & Stöggl, 2019; Mayer, et al., 2014, 2016; Ozmen & Aydogmus, 2016; Sannicandro, 2017; Shamsi, et al., 2016; Toprak Çelenay & Özer Kaya, 2017), and five of these studies specified the participants' sex and managed data separately (Aggarwal, et al., 2010; Mayer, et al., 2014, 2016; Shamsi et al., 2016; Toprak Çelenay & Özer Kaya, 2017). Four studies included only male athletes (Jamison, et al., 2012; Stanton, et al., 2004a; Tse, et al., 2005; Weston, et al., 2013), only one comprised a female sample (Kuhn, et al., 2019), and another one did not specify the sex of the participants (Lust, et al., 2009). The participants chronological age varied from 10.8 to 66.4 years. Seven studies included athletes from different sports (American football, handball, baseball, badminton, basketball, touch

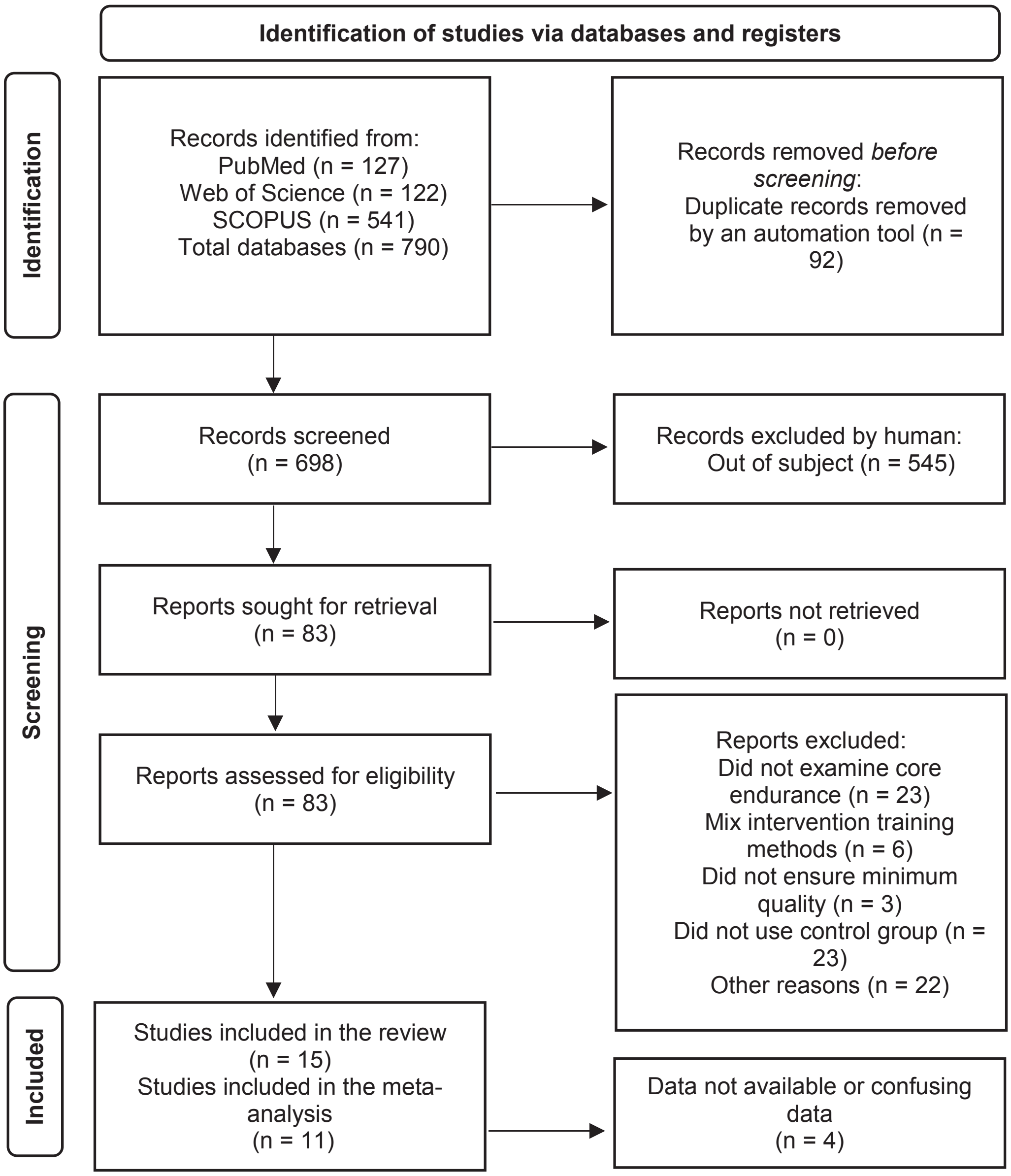

Figure 1. PRISMA flow diagram.

football, rowing, and golf) (Jamison, et al., 2012; Kuhn, et al., 2019; Lust, et al., 2009; Ozmen & Aydogmus, 2016; Stanton, et al., 2004a; Tse, et al., 2005; Weston, et al., 2013). Four articles selected active healthy people as participants (Aggarwal, et al., 2010; Junker & Stöggl, 2019; Sannicandro, 2017; Toprak Çelenay & Özer Kaya, 2017). Only one study used firefighters (Mayer, et al., 2014), and another one soldiers (Mayer, et al., 2016). Two studies comprised participants with different health problems, poor core stability (Chuter, et al., 2015) and chronic LBP (Shamsi, et al., 2016).

Six studies used only bodyweight exercises to carry out specific trunk training (Junker & Stöggl, 2019; Mayer, et al., 2014; Sannicandro, 2017; Shamsi, et al., 2016; Tse, et al., 2005; Weston, et al., 2013). The most utilised equipment was the Swiss ball, used in seven out of 15 articles included in this SRMA (Aggarwal, et al., 2010; Chuter, et al., 2015; Kuhn, et al., 2019; Lust, et al., 2009; Ozmen & Aydogmus, 2016; Stanton, et al., 2004a; Toprak Çelenay & Özer Kaya, 2017). One of these seven studies used only a Swiss ball to perform all exercises (Stanton, et al., 2004a). Medball, resistance bands and other unstable surfaces were the equipment selected in the rest of the training methodologies (Aggarwal, et al., 2010; Chuter, et al., 2015; Jamison, et al., 2012; Kuhn, et al., 2019; Mayer, et al., 2016; Ozmen & Aydogmus, 2016; Toprak Çelenay & Özer Kaya, 2017). Duration of training varied between five to 24 weeks, one to three sessions per week, 11 to 48 total sessions, 1 to 4 sets and 5 to 20 repetitions, or 6 to 105 seconds. Regarding the exercises, a great variation was found between training methodologies. Different sides planks were the most selected exercises in training programmes. The two

Table 1. Studies included in the systematic review and meta-analysis

Author/s (year)	EXPERIMENTAL group	CONTROL group	CORE training	Training material	Duration	Tests / Outcome	Effect
Aggarwal, Kumar and Kumar (2010)	Active male (n=10) and female (n=10) 24.62 y.o.	Active male (n=10) and female (n=10) 23.85 y.o.	Abdominal muscle contractions (different positions), bird -dog, superman, multi direction lunges, twists, front planks, oblique pulleys, different crunches and back bridges	Medball, Swiss ball and BW	6 weeks, 3 days/ week, 18 total sessions, 40-50 min, 1-3 sets, 10-20 reps	TF (sec) TE (sec) RP (sec) LP (sec) PP (sec)	↑ ↑ ↑ ↑ ↑
Celenay and Kaya (2017) *	Active male (n=13) and female (n=15) 21 y.o.	Active male (n=13) and female (n=12) 20.36 y.o.	Thoracic bracing (supine, prone, side lying, quadrupedal, and bipedal) with upper and lower movements	BW, resistance band and Swiss ball	8 weeks, 45 min, 3 sets, 10-15 reps	TF (sec) TE (sec) RP (sec) LP (sec)	↑ ↑ ↑ ↑
Chuter et al., (2015) *	Male and female with poor core stability (n=26) 26.31 y.o. Male and female with poor core stability (n=26) 25.22 y.o. (home CORE)	Male and female with poor core stability (n=26) 27.01 y.o.	Cat/camel, abdominal contraction, side bridge, dead bug, bird dog, hip abduction, swiss ball abdominal isometric, lunges and different trunk twists with band resistance and swiss ball	BW, resistance band and Swiss ball	8 weeks, 2 days/ week, 16 total sessions, 2-3 sets, 10-15 reps or 15-105 secs	TF (sec) TE (sec) Lateral bridge (sec)	↑ ↑ ↑
Jamison et al. (2012)	Male American football players (n=10) 20.5 y.o.	Male American football players (n=11) (RT) 20.3 y.o.	Prone planks, side planks, front, back and side lunges, sagittal and diagonal abdominal curls, hip abduction, quadruped exercises and supine exercises	BW and dumbbells	6 weeks, 60 min, 3 days/week, 18 total sessions	TF (sec) TE (sec) Side bridge (sec)	↑ ↑ ↑
Junker and Stoggl (2019)	Male and female recreationally active (n=11) 28.2 y.o.	Male and female recreationally active (n=12) 29.1 y.o.	Plank, side plank, back bridge, quadruped, back extension.	BW	8 weeks, 2 days/ week, 16 total sessions, 3 sets of 15-50 sec	Dynamic PP (sec) TE movement (sec) Dynamic side bridge (sec)	↔ ↑ ↑
Kuhn, Weberrub and Horstmann (2019) *	Female handball recreational players (n=10) 24.1 y.o.	Female handball recreational players (n=10) 23.7 y.o.	Plank push-up, sit-up, side plank prone plank and quadruped stance variations, prone plank, shoulder bridge, back extension	Swiss ball and unstable surface	6 weeks, 2 days/ week, 12 total sessions, 2 sets of 45 sec, 1 min rest	TF movement (sec) TE movement (sec) RP movement (sec) LP movement (sec)	↔ ↔ ↑ ↑
Lust et al. (2009)	Baseball players average (n=11) 20 y.o.	Baseball players average (n=8) 20 y.o.	Dead bug, partial sit-ups, bridging, prone exercises, quadruped exercises, wall slides, and ball exercises	BW and Swiss ball	6 weeks, 18 total sessions, 3 days/ week, 2 sets, 30-105 secs	TF (sec) TE (sec) RP (sec) LP (sec)	↔ ↔ ↔ ↔
Mayer et al. (2014)	Male (n=52) and female (n=2) firefighters 37.6 y.o.	Male (n=35) and female (n=7) firefighters 31.3 y.o.	Cat-camel, birddog, curl-up, side bridge and Roman chair back extension	BW	24 weeks, 2 days/ week, 48 total sessions, 1 set/ exercise, 5 reps	TE (sec) PP (sec)	↑ ↑
Mayer et al. (2016)	Male (n=266) and female (n=68) Texas soldiers 21.5 y.o.	Male (n=231) and female (n=67) Texas soldiers (n= 298) 21.8 y.o. (lumbar extension high intensity training)	Abdominal drawing-in crunch maneuver, horizontal side support, supine shoulder bridge, quadruped alternating arm and leg, and woodchopper	BW and resistance band	11 weeks, 1 day/ week, 11 total sessions, 1 set / exercise, 6 reps	Lumbar extension (reps) PP (sec)	↓ ↔

Table 1. Studies included in the systematic review and meta-analysis

Author/s (year)	EXPERIMENTAL group	CONTROL group	CORE training	Training material	Duration	Tests / Outcome	Effect
Ozmen and Aydogmus (2016)	Male and female badminton players (n=10) 10.9 y.o.	Male and female badminton players (n=10) 10.8 y.o.	Abdominal bracing, hollowing, prone, supine and side bridge, quadruped alternate-arm leg raises, seated marching, crossover crunch, dead-bug, superman and twist	BW, Swiss ball and Medball	6 weeks, 2 days/ week, 12 total sessions, 10-20 reps, 4 exercises each session	TF (sec)	↑
						TE (sec)	↑
						Lateral bridge (sec)	↑
Sannicandro (2017)	Active male and female (n=33) 66.4 y.o.	Active male and female (n=32) 66.2 y.o. (aerobic)	Plank, side plank, climber, prone plank, supine bridge and quadruped leg raises	BW	8 weeks, 3 days/ week, 24 total session, 3-4 sets, 6-8 reps or 6 secs	TF (sec)	↑
						TE (sec)	↑
						RP (sec)	↔
						LP (sec)	↑
Shamsi et al. (2016)	Male (n=7) and female (n=15) with chronic LBP 39.2 y.o.	Male (n=6) and female (n=15) with chronic LBP 47.9 y.o (general body exercises)	4 sessions → cognition of local muscle contraction sessions; 6 sessions → low contractions, isometric and minimal loaded position sessions and last 6 sessions → functional tasks with heavier loads sessions	BW	5-6 weeks, 20 min, 16 sessions 3 days per week	TF (sec)	↔
						TE (sec)	↔
						RP (sec)	↔
						LP (sec)	↔
Stanton, Reaburn and Humphries (2004)	Basketball and touch football male (n=11)15.6 y.o.	Basketball and touch football male (n=11)15.5 y.o.	Lunge, supine lateral roll, alternating superman, forward roll on knees, supine 2 leg bridge and supine Russian twist	Swiss ball	6 weeks, 2 days/ week, 12 total sessions, 2-3 sets, 10 reps, ↑volume each 2 week	Swiss ball prone stability test (sec)	↑
Tse et al. (2005)	Male rowers (n=25) 21 y.o.	Male rowers (n=20) 20.01 y.o.	Stability exercise → Static/dynamic → Controlled mobility	BW	8 weeks, 2 days/ week, 16 total sessions, 10-40 min	TF (sec)	↔
						TE (sec)	↔
						RP (sec)	↑
						LP (sec)	↑
Weston, Coleman and Spears (2013) *	Club male golfers (n=18) 47 y.o.	Club male golfers (n=18) 47 y.o.	Double-leg squat, bent-leg curl up, superman, supine bridge, prone bridge, quadruped, lunge, and side bridge	BW	8 weeks, 3 days/ week, 24 total sessions	TF (sec)	↑

Notes. y.o.= years old; sec= seconds; LBP= low back pain; REP = repetitions; ↑ : significantly improved EXPERIMENTAL; ↔ : not significantly improved; ↓ significantly improved CONTROL; BW: body weight; *: articles not included in the meta-analysis; TF: trunk flexion; TE: trunk extension; PP: prone plank; RP: right plank; LP: left plank.

studies that included the medball in the training programme improved all core muscle endurance measured in their investigation, trunk flexion, extension and both lateral (Aggarwal, et al., 2010; Ozmen & Aydogmus, 2016). In addition, methodologies that included resistance bands or dumbbells improved all measures of core muscle endurance (Chuter, et al., 2015; Jamison, et al., 2012; Toprak Çelenay & Özer Kaya, 2017). Only one study performed with soldiers, which included resistance bands in their training, did not show improvements in the prone plank test (Mayer, et al., 2016). Five weeks of training seemed ineffective in improving core muscle endurance in LBP patients (Shamsi, et al., 2016). However, six weeks of treatment showed improvements in most studies that used different types of healthy samples (Aggarwal, et al., 2010; Jamison, et al., 2012; Ozmen & Aydogmus, 2016; Stanton, et al., 2004b). Regarding total sessions in programmes, the three studies that used 24 total sessions or more showed improvements in all of their core muscle endurance measures except in trunk extension in Sannicandro study (Mayer, et al., 2014; Sannicandro, 2017; Weston, et al., 2013).

To measure the anterior muscles of core muscle endurance, predominantly rectus and transversus abdominis, the most selected test was the flexion endurance test in ten studies (Aggarwal, et al., 2010; Chuter, et al., 2015; Jamison, et al., 2012; Lust, et al., 2009; Ozmen & Aydogmus, 2016; Sannicandro, 2017; Shamsi, et al., 2016; Toprak Çelenay & Özer Kaya, 2017; Tse, et al., 2005; Weston, et al., 2013), and the prone plank test in three studies (Aggarwal, et al., 2010; Mayer, et al., 2014, 2016). In addition, one study used dynamic prone plank (with movement) (Junker & Stöggl, 2019), another analysed the dynamic trunk flexion (with movement) (Kuhn, et al., 2019), and the last one used prone plank on an instability platform (Swiss ball) (Stanton, et al., 2004a). To assess the posterior values of core muscle endurance, predominantly *multifidus* and *transversus abdominis*, the most selected test was the trunk extension endurance test in ten studies (Aggarwal, et al., 2010; Chuter, et al., 2015; Jamison, et al., 2012; Lust, et al., 2009; Mayer, et al., 2014; Ozmen & Aydogmus, 2016; Sannicandro, 2017; Shamsi, et al., 2016; Toprak Çelenay & Özer Kaya, 2017; Tse, et al., 2005). Two studies used dynamic trunk extension (with movement) (Junker & Stöggl, 2019; Kuhn, et al., 2019), and another one used a lumbar dynamometer machine to quantify repetitions of trunk extensions (Mayer, et al., 2016). To quantify lateral sides of core muscle endurance, mainly internal and external obliques and *transversus abdominis*, the most selected test was right and left plank endurance tests in six studies (Aggarwal, et al., 2010; Lust, et al., 2009; Sannicandro, 2017; Shamsi, et al., 2016; Toprak Çelenay & Özer Kaya, 2017; Tse, et al., 2005). Three studies did not separate the right and left sides and only measured one side (Chuter, et al., 2015; Jamison, et al., 2012; Ozmen & Aydogmus, 2016), and two articles used dynamic side endurance tests (with movement) (Junker & Stöggl, 2019; Kuhn, et al., 2019).

Main analysis

Eleven studies provided data for core flexion endurance (pooled n = 822). Compared to the control condition, there was a moderate effect of intervention on core flexion endurance (ES = 0.67; 95% CI = 0.19 to 1.16; p=.006; I^2 = 87.2%; Egger's test p=.056; Figure 2). The relative weight of each study in the analysis ranged from 6.9% to 11.3%.

Nine studies provided data for core extension endurance (pooled n = 746). Compared to the control condition, there was a small effect of intervention on core extension endurance (ES = 0.49; 95% CI = -0.08 to 1.06; p=.094; I^2 = 90.0%; Egger's test p=.110; Figure 3). The relative weight of each study in the analysis ranged from 9.6% to 13.1%.

Study name	Statistics for each study						
	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Aggarwal. Kumar and Kumar (2010)	3.496	0.499	0.249	2.518	4.474	7.008	0.000
Jamison et al. (2012)	0.058	0.420	0.176	-0.764	0.881	0.139	0.890
Lust et al. (2009)	-0.107	0.444	0.197	-0.978	0.763	-0.241	0.809
Mayer et al. (2014)	0.500	0.219	0.048	0.071	0.928	2.286	0.022
Mayer et al. (2016)	-0.032	0.094	0.009	-0.216	0.152	-0.341	0.733
Ozmen and Aydogmus (2016)	2.552	0.588	0.346	1.398	3.705	4.337	0.000
Sannicandro (2017)	1.005	0.260	0.068	0.494	1.515	3.857	0.000
Shamsi et al.. (2016)	0.274	0.301	0.091	-0.316	0.864	0.910	0.363
Tse et al. (2005)	-0.053	0.347	0.121	-0.734	0.628	-0.152	0.879
Stanton. Reaburn and Humphries (2004)	0.338	0.413	0.171	-0.472	1.148	0.818	0.413
Junker and Stoggl (2019)	0.286	0.405	0.164	-0.507	1.079	0.707	0.479
	0.672	0.247	0.061	0.189	1.155	2.725	0.006

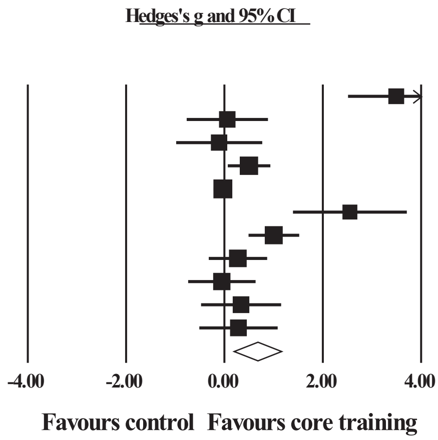

Figure 2. Forest plot of changes in core flexion endurance after the core training compared to the control condition. Values shown are effect sizes with 95% confidence intervals (CI). Black boxes: individual study groups. White diamond: overall result. The relative weight of each study in the analysis is indicated by the size of the plotted box in the figure.

Study name	Statistics for each study						
	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Aggarwal. Kumar and Kumar (2010)	3.256	0.478	0.229	2.319	4.193	6.810	0.000
Junker and Stoggl (2019)	0.547	0.410	0.168	-0.257	1.351	1.333	0.182
Lust et al. (2009)	-0.816	0.463	0.215	-1.724	0.092	-1.762	0.078
Mayer et al. (2014)	0.526	0.219	0.048	0.097	0.955	2.404	0.016
Mayer et al. (2016)	-0.252	0.098	0.010	-0.444	-0.060	-2.569	0.010
Ozmen and Aydogmus (2016)	1.505	0.490	0.240	0.545	2.466	3.072	0.002
Sannicandro (2017)	0.481	0.249	0.062	-0.006	0.969	1.934	0.053
Shamsi et al.. (2016)	0.249	0.301	0.090	-0.340	0.838	0.829	0.407
Tse et al. (2005)	-0.646	0.357	0.127	-1.345	0.053	-1.810	0.070
	0.487	0.291	0.085	-0.083	1.057	1.675	0.094

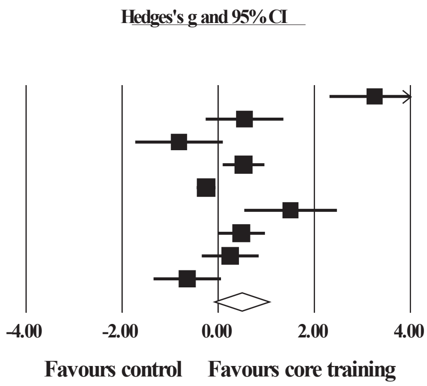

Figure 3. Forest plot of changes in core extension endurance after the core training compared to the control condition. Values shown are effect sizes with 95% confidence intervals (CI). Black boxes: individual study groups. White diamond: overall result. The relative weight of each study in the analysis is indicated by the size of the plotted box in the figure.

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
	Statistics for each study						
Aggarwal. Kumar and Kumar (2010)	1.575	0.356	0.127	0.876	2.274	4.418	0.000
Lust et al. (2009)	-0.094	0.444	0.197	-0.964	0.777	-0.211	0.833
Sannicandro (2017)	1.590	0.282	0.080	1.037	2.143	5.638	0.000
Shamsi et al.. (2016)	-0.171	0.300	0.090	-0.760	0.417	-0.571	0.568
Tse et al. (2005)	0.857	0.364	0.132	0.145	1.570	2.358	0.018
	0.767	0.398	0.158	-0.013	1.547	1.926	0.054

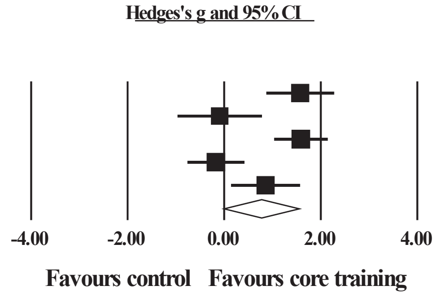

Figure 4. Forest plot of changes in core right-lateral endurance after the core training compared to the control condition. Values shown are effect sizes with 95% confidence intervals (CI). Black boxes: individual study groups. White diamond: overall result. The relative weight of each study in the analysis is indicated by the size of the plotted box in the figure.

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
	Statistics for each study						
Aggarwal. Kumar and Kumar (2010)	2.814	0.442	0.195	1.948	3.679	6.371	0.000
Lust et al. (2009)	-0.888	0.467	0.218	-1.803	0.026	-1.904	0.057
Sannicandro (2017)	1.907	0.297	0.088	1.325	2.489	6.426	0.000
Shamsi et al.. (2016)	-0.129	0.300	0.090	-0.717	0.458	-0.432	0.666
Tse et al. (2005)	0.972	0.368	0.135	0.251	1.694	2.642	0.008
	0.939	0.611	0.373	-0.258	2.135	1.537	0.124

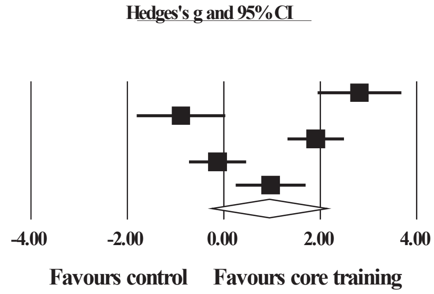

Figure 5. Forest plot of changes in core left-lateral endurance after the core training compared to the control condition. Values shown are effect sizes with 95% confidence intervals (CI). Black boxes: individual study groups. White diamond: overall result. The relative weight of each study in the analysis is indicated by the size of the plotted box in the figure.

Five studies provided data for core right-lateral endurance (pooled n = 199). Compared to the control condition, there was a small effect of intervention on core right-lateral endurance (ES = 0.77; 95% CI = -0.01 to 1.55; p=.054; I^2 = 85.2%; Egger's test p=.651; Figure 4). The relative weight of each study in the analysis ranged from 18.3% to 21.2%.

Five studies provided data for core left-lateral endurance (pooled n = 199). Compared to the control condition, there was a moderate effect of intervention on core left-lateral endurance (ES = 0.94; 95% CI = -0.26 to 2.14; p=.124; I^2 = 92.3%; Egger's test p=.966; Figure 5). The relative weight of each study in the analysis ranged from 19.2% to 20.6%.

Discussion and conclusions

The purpose of this SRMA was to assess the effects of trunk training on different core muscle endurance measurements (flexion, extension, right and left lateral flexion). Quantitative results showed a significant effect of trunk training on flexion core muscle endurance with a moderate effect (ES = 0.67), including eleven studies with 822 participants. However, extension core muscle endurance showed a small effect after trunk training intervention (ES = 0.49) with 746 participants in nine studies. In addition, right-lateral endurance and left-lateral endurance displayed moderate effects (ES = 0.77 and ES = 0.94, respectively) after core programmes analysed in five studies with 199 subjects.

Core flexion endurance

The data showed that the trunk training group moderately improved flexion endurance compared to the control group/condition. The most favourable results in favour of the experimental group could be seen in the studies conducted by Aggarwal et al. (2010) and Ozmen and Aydogmus (2016). These studies used similar training methodologies, with six weeks of intervention with 2-3 days per week and 12 or 18 total sessions. In addition, exercise selection in each programme had some similarities; the experimental group started their training programme with isolated exercises like abdominal contractions in different positions (Aggarwal, et al., 2010; Ozmen & Aydogmus, 2016). Additionally, equipment registered in these two studies were the same—med ball, Swiss ball and body weight exercises. In each week the progression towards more difficult exercises was applied until finalised with instability tasks. However, other training methodologies with not-so-good results, like the Stanton et al. (2004) study programme, used instability exercises performed with a Swiss ball from the first session for all tasks performed. Besides good training programmes, there may be the other reason to explain the better results of these two studies—it could be the participants fitness level. Ozmen and Aydogmus (2016) study used teenagers, and Aggarwal et al. (2010) used active people not being highly trained subjects. This could be the main reason to explain the better results of these studies; young people are more sensitive to a new stimulus. Also, the untrained subjects' improvements are usually seen after the application of almost any type of training. The third best result of MA in flexion endurance also supports this reason—the Sannicandro sample also used an active male and female sample (Sannicandro, 2017). In contrast, Jamison et al. (2012), Lust et al. (2009), Mayer et al. (2016), and Tse et al. (2005) have not shown much improvement in their control groups in flexion core muscle endurance. Neither of these four studies has an untrained sample; the participants were American football players, baseball players, soldiers, and rowers. Core muscle endurance flexion is probably an essential movement during their activities despite not being specifically trained. This sentence could be supported by the Weston, Coleman, and Spears (2013) study where male golfers performed mainly isometric trunk training for eight weeks, three days per week and showed improvements in trunk flexion endurance in the experimental group. The authors of this study discuss the transfer of this type of training to golf performance because trunk flexion is not mainly a movement in their sport. This makes them having a previous better core flexion endurance, and the effect of the training may not be as clear as in other subjects.

Core extension endurance

The results of this paper exposed that the trunk training group improved with a small effect concerning the control group/condition in extension endurance. Despite the improvement shown, three studies did not obtain improvements in this parameter with respect to the control group, which got a bit worse (Lust, et al., 2009; Mayer, et al., 2016; Tse, et al., 2005). The Lust et al. (2009) training methodology used open and closed kinetic chain exercises in the experimental and control group but added specific core exercises to the experimental group. Baseball players' fitness level in the Lust et al. (2009) study was higher than the level of the sample in Aggarwal et al. (2010) that showed the best improvement in core extension endurance parameter. The same argument could be applied to the Mayer et al. (2016) and Tse et al. (2005) participants, soldiers and rowers, respectively, that did not show improvement in this task. In addition, in the Tse et al. (2005) study methodology, participants in the control group/condition included some basic training rower exercises that involved traditional trunk extensions on apparatus. In the same way, Mayer et al. (2016) control group/condition performed lumbar extensor high-intensity progressive resistance exercise. These two specific methodologies could be the main reason for the improvement in this parameter in favour of the control group for these two studies. Probably would, after excluding these two studies, the effect of trunk training on extension endurance increase from small to moderate. Equally, participants in a trunk training programme started at a level of difficulty that was consistent with their current fitness level to get the most out of the trunk extension endurance exercises.

Core lateral endurance

The data showed that the trunk training group improved moderately with respect to the control group/condition in core-right lateral endurance. The two studies in which this parameter was most improved concerning the control group/condition were Aggarwal et al. (2010) and Sannicandro (2017) and were the unique two studies that did not include a highly trained population but active male and female participants that did not practice any specific sport. These two samples probably had a lower initial fitness level than baseball players (Lust, et al., 2009). Furthermore, male rowers (Tse, et al., 2005) showed high improvements in this parameter compared to flexion or extension core muscle endurance. The authors argue that the main reason for these results was that flexion and extension movements are used quite often in the rowing movement, primarily in the sagittal plane. In contrast, lateral flexion movements are not specifically carried out in the normal rowing stroke. The same argument could explain the similar results shown in female handball players whose core trunk flexion, extension, and right and left flexion endurance were measured with distal movements until exhaustion tests and only showed improvements in right and left flexions with respect to the control group/condition (Kuhn, et al., 2019).

The data showed that the trunk training group improved moderately compared to the control group/condition in left-lateral movement muscular endurance. In the same way, as in the right-lateral movement muscular endurance, Aggarwal et al. (2010) and Sannicandro (2017) studies showed the best improvement in this parameter and Lust et al. (2009) and Shamsi et al. (2016) methodologies did not enhance with respect to the control group/condition. Baseball players often use rotational trunk movements that involve flexion of core muscles, mainly on their dominant side (Lust, et al., 2009). That could be why this sample did not improve in these parameters; in addition, right core muscle endurance flexion showed less improvement than the left side, and it could be that most of the players were probably right-handed. Regarding Shamsi et al. (2016), which involved LBP patients, the control group/condition performed general exercises. It showed some left and right flexion core muscle endurance improvement concerning the experimental condition. That could be because, in the LBP patients, trunk training targets were too aggressive, and they did not have the fitness level to perform it correctly.

This SRMA analysed four types of trunk movements regarding core muscle endurance—flexion, extension, and right and left flexion. The exciting finding was that the trunk training improved the four core muscle endurance measures—flexion, right flexion and left flexion moderately and in extension there was a small improvement. The slightest improvement in extension movement could result from some training methodologies or samples analysed. Due to the core muscles function being hubs in the biological motor chain, which create a fulcrum for the four limbs' strength and establish a channel for the cohesion, transmission, and integration of the upper and lower limbs, core training should be included in training sessions to improve athletic performance. However, according to Dong, Yu, and Chun (2023), it is necessary to adequately design core training programmes to improve sport-specific athletic performance. For example, rotational trunk movements are essential to improve performance in sports like boxing, thus, this type of movement analysis could be a limitation in this SRMA.

To the authors' knowledge, this is the first SRMA to assess the effects of trunk training on core muscle endurance in a healthy population. In the current SRMA, 649 experimental and 564 control participants were involved. This could reduce the problem of underpowered sample studies. There are currently a limited number of randomised controlled trials investigating the effects of core training on core muscle endurance not assessed with the trunk extension, flexion, right or left flexion isometric tests proposed by McGill et al. (1999). Despite the advantages of these tests, the present study results could be skewed by their advantages and disadvantages. Therefore, the results of this study should not be generalised to all populations; only one study with LBP patients was included in this SRMA (Shamsi, et al., 2016). Due to the physiological differences between the sexes, future studies should analyse the differences between men and women in core muscle endurance. Despite these limitations, the current SRMA makes an original contribution to the literature and presents for consideration the influence of core training on core muscle endurance.

Practical applications

Strength and conditioning coaches should be aware that core training improves core muscle endurance performance. However, the athletes' previous fitness level and their previous training of the specific movements is determinant in the core muscle endurance improvement. Both, athletes and healthy people should integrate this type of training into their programmes. Athletes may try to improve performance and reduce the risk of injury, while healthy people try to reduce the risk of falls and pursue to move better in their daily life tasks. Concerning the core training, it should be supervised to ensure the correct execution of exercises; a programme should be based on proper progression and suitable exercise selection that involve four basic core movements (flexion, extension, right flexion and left flexion). To show better performance after core training, athletes need to train their specific trunk weak movements to reduce compensations caused by their specific sports. Progression programmes with exercises and equipment variations seem to be more effective.

The results of this SRMA support the notion that trunk training improves core muscle endurance in four principal movements (trunk flexion and extension and right and left flexion). However, to back up the results presented in this study, more research into the effects of trunk training on core muscle endurance is needed. The higher benefits are found in trunk flexion and right and left flexion measurements. The trunk extension endurance improves with a small effect. This SRMA hypothesised that most trained movements during training methodologies would improve more. In addition, in movements with poor results in pre-intervention, core training could be more effective. Adding training equipment like medballs, resistance bands or dumbbells to increase difficulty could be a good choice. Thus, athletes with poor previous fitness level benefited more from this type of training than high-trained athletes.

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COMPARATIVE STUDY OF POSITIONING AND TECHNICAL-TACTICAL INDICATORS BETWEEN TEAMS OF DIFFERENT PERFORMANCE LEVELS IN THE QATAR 2022 FIFA WORLD CUP

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Abstract:

The aim of the study was to identify the technical-tactical indicators and differentiate collective positioning between the qualified teams and teams non-qualified for the final phase of the FIFA World Cup Qatar 2022, considering effective playing time. The aim was also to understand the interaction of variables that significantly increased the likelihood of being qualified in the analysed championship. We conducted a comparative analysis that covered all matches played (N=64), evaluating 93 technical-tactical indicators, 24 collective positional indicators and six hybrid indicators. The absolute technical-tactical indicators were normalised based on the effective playing time of each team in each match. We used t-tests and binary logistic regression (R2 Nagelkerke = .738 – AUC = .955) to analyse differences and determine their statistical significance (p<.05). Our analysis revealed significant differences in 33 indicators, suggesting that certain technical-tactical aspects played a crucial role in teams' performance. Furthermore, through multivariate analysis, we were able to identify that offensive efficiency in set pieces, the height of the defensive line during the offensive phase, and the ability to reduce the available playing space for the opposing team during the defensive phase emerged as the main indicators that allowed us to classify the teams' performance. These findings enable coaches to use the identified key indicators as performance predictors to devise match strategies aimed at enhancing the effectiveness of their teams.

Keywords: *FIFA World Cup, key performance indicators, multivariate analysis, match analysis*

Introduction

Examining and analysing the tactical behavior of teams, as well as conducting comparative analyses between groups of different performance levels, enables us to identify the main tactical differences between these groups. Consequently, we can determine the key performance indicators (KPIs) in football (Hughes & Bartlett, 2002), establishing them as variables that contribute to success (Hughes & Bartlett, 2008). The interpretation of these data enables coaches to understand the patterns of behavior and organization of teams with the highest success rates, providing them with information to design match strategies, game systems, and training tasks (Casal, et al., 2021a).

Recognizing the significance of this information, several previous studies compared the technical-tactical behavior of successful and unsuccessful teams, leading to the identification of some KPIs. For instance, the total number of shots and shots on target emerged as fundamental discriminative variables between winning, losing, and drawing teams in various studies (Carling, Le Gall, McCall, Nédélec, & Dupont, 2015; Casal, Losada, Barreira, & Maneiro, 2021b; Castellano, Casamichana, & Lago, 2012; García-Rubio, Gómez, Lago-Peñas, & Ibáñez, 2015; Liu, Gómez, Lago-Peñas, & Sampaio, 2015; Moura, Martins, & Cunha, 2014). Additionally, total passes, accurate passes, and total passes in the opposition half were identified as robust indicators to differentiate teams' performance (Carling, et al., 2015; Casal, et al., 2021b; Collet, 2013; Gómez, Mitrotasios, Armatas, & Lago-Peñas, 2018; Harrop & Nevill, 2014; Paixão, Sampaio, Almeida, & Duarte, 2015; Praça, Brandão, de Oliveira Abreu, Oliveira, & de Andrade, 2023), observing typically higher values for these variables in teams with better performance.

In direct relation to the number of passes, ball possession has been identified as a distinctive tactical indicator among teams in various studies (Bradley, Lago-Peñas, Rey, & Sampaio, 2014; Carling, et al., 2015; Casal, Maneiro, Ardá, Marí, & Losada, 2017; Casal, et al., 2021b; Collet, 2013; Liu, Hopkins, & Gómez, 2016; Moura, et al., 2014). All studies agree that longer ball possession characterized higher-ranked teams. However, when considering ball possession in the context of the match status, conclusive results were not obtained. Some studies suggested that teams tended to have more possession when they were winning (Fernandez-Navarro, Fradua, Zubillaga, & McRobert, 2019), while others indicated the opposite (Paixão, et al., 2015). What some studies (Casal, et al., 2021b; Fernandez-Navarro, et al., 2019; Lago-Ballesteros, Lago-Peñas, & Rey, 2012; Winter & Pfeiffer, 2016) confirmed is that teams exhibited different playing styles based on the match status, with some teams modifying their style accordingly, while others maintained it unchanged.

The way goals were scored, and the quality of opponent teams was also identified as differentiating indicators among teams (Lago-Peñas, Gómez-Ruano, Megías-Navarro, & Pollard, 2016). In general, teams that scored first were more likely to win, and facing lower-level opponents increased winning rates. On the other hand, some studies have focused on the analysis of specific defensive indicators. In particular, the type and location of ball recovery were examined as differentiators of team performance (Almeida, Ferreira, & Volossovitch, 2014; Gómez, et al., 2018; Winter & Pfeiffer, 2016). Their findings indicate that higher-ranked teams were more effective than lower-ranked ones in applying defensive pressure in advanced field positions.

Despite the work done so far, in the case of some performance indicators, such as ball possession, making definitive statements is challenging due to the diversity and, on some occasions, contradictions in study results. This circumstance can be explained, in part, by methodological differences among various studies and possible conceptual errors. For instance, most previous works categorized team performance based on match outcomes, when it might be more appropriate to perform them according to the final ranking in a competition (Casal, et al., 2021b). This approach aligns with the methodology employed by Almeida et al. (2014), Bradley et al. (2014), Casal et al. (2021b), Castellano et al. (2012), Collet (2013), Liu et al. (2016) and, additionally, the importance of studies following a nomothetic and longitudinal approach, as indicated by Casal et al. (2021b), has been recognized to identify KPIs and patterns of team playing strategies. This approach involves analysing multiple teams participating in a competition over several matches, allowing for more effective identification and understanding of these teams' behavioral patterns.

Furthermore, Phatak et al. (2022) emphasize the importance of normalizing data to accurately identify KPIs. This process is crucial as data in its absolute form can lead to inadequate conclusions. Normalization involves considering the real action time during a football match, accounting for interruptions like corner kicks, player substitutions, injuries, or deliberate time-wasting. By dividing statistics by effective playing time, this approach provides a more accurate and fair perspective of teams' or players' performance, regardless of possession time or active involvement in the game. The aim is to calculate the rate or frequency of events per minute of effective playing time, facilitating a fair comparison and evaluation between teams and players and highlighting performance patterns in relation to real playing time.

Furthermore, it must be considered that football is a sport that represents a completely dynamic system in constant transformation and evolution. Therefore, it is crucial to keep such studies updated to reflect current trends in teams' play and evaluate whether there have been any changes compared to the past.

Based on all the above, the aim of this study was to identify the technical-tactical indicators as well as the differences in collective positioning between the teams qualified and the teams not qualified for the final phase of the FIFA World Cup 2022 considering the effective playing time. Additionally, we aimed to understand the interaction of variables that increased the likelihood of qualifying for the said phase in the analysed championship. In an effort to address some of the shortcomings in previous studies, data normalization based on effective playing time was applied.

Materials and methods

Sample

In this study, all the teams (N=32) and all the matches played (N=64) in the FIFA World Cup Qatar 2022 were analysed and in each one, both teams were observed. Data were extracted from InstatScout (not available now), currently WyScout (https://platform.wyscout.com/app/?) and FIFA (http://fifa.com). These providers have demonstrated their validity and reliability in previous studies (Bradley, 2023; Casal, et al., 2021b; Gómez, et al., 2018; Silva & Marcelino, 2023).

Procedure

All the KPIs analysed are presented in Table 1. The operational definitions of the variables extracted from the Instat Scout can be found in Appendix 1. The graphical definitions of the variables obtained from post-match reports can be consulted in FIFA (2023). Following the procedure of contextualization and normalization of the data proposed by Phatak et al. (2022), the technical-tactical indicators were normalised based on the effective playing time (obtained from Instat) of each match. In this way, the absolute KPIs were transformed into KPIs per minute of effective playing time.

The positional variables related to the area (m^2) were synthetically created by multiplying the average width and length for each of the analysed positions, resulting in the area (in square meters) occupied by the external players of the team, excluding the goalkeeper. The analysed teams were categorized according to the final classification in a dichotomous variable (1 = qualified for the round of 16, 0 = non-qualified) as previous studies did (Almeida, et al., 2014; Bradley, et al., 2014, Casal, et al., 2021b, Castellano, et al., 2012, Collet, 2013; Liu, et al., 2016).

Data analysis

First, a t-test for independent samples was performed to compare the qualified and non-qualified teams in terms of each variable evaluated.

$$KPI\ (norm) = \frac{Absolute\ Value\ KPI}{Effective\ Playing\ Time} \rightarrow \text{Passes per minute} = \frac{Total\ Passes}{Effective\ Playing\ Time}$$

Table 1. The technical-tactical indicators analysed

Main statistics	- Goals - Chances - Chances successful - Fouls - Yellow cards - Red cards - Offsides - Corners - Corners with shots - % efficiency for corner attacks* - Total actions - Successful actions - Shots - Shots on target - Shots off target - Shots blocked - xG – Opponent's xG.
Passes	- Passes - Accurate Passes - Accurate passes %* - Key passes - Accurate Key passes - Crosses - Accurate crosses.
Challenges	- Challenges - Challenges won - Challenges won %* - Defensive challenges - Defensive challenges won - Defensive challenges won %* - Attacking challenges - Attacking challenges won - Attacking challenges won %* - Air challenges - Air challenges won - Air challenges won %* - Dribbles - Dribbles successful - Dribbles successful %* - Tackles - Tackles successful - Tackles successful %*.
Ball losses and recoveries	- Ball interceptions - Free ball pickups - Lost balls - Lost balls in the own half - Ball recoveries - Ball recoveries in the opponent's half.
Offensive efficiency	- Entrances to the opposition half - Entrances to the final third - Entrances to the penalty box - Ball possessions (quantity) - Average possession time*.
Defensive efficiency*	- Team pressing - Team pressing successful - Pressing efficiency (%) - Building-ups - Building-ups without pressing - High pressing - High pressing successful - High pressing (%) - Low pressing - Low pressing successful - Low pressing successful (%).
Attacks typology	- Positional attacks - Positional attacks with shots - Positional attacks efficiency (%)* - Counterattacks - Counterattacks with shots - Counterattacks efficiency (%)* - Set pieces attacks - Set pieces attacks with shots - Set pieces attacks efficiency (%)* - Attacks through the left flank - Attacks through the left flank with shots - Efficiency of attacks through the left flank (%)* - Attacks through the center flank - Attacks through the center flank with shots - Efficiency in attacks through the center flank (%)* - Attacks though the right flank - Attacks through the right flank with shots - Efficiency in attacks through the right flank (%)*- Throw in attacks - Throw in attacks with shots - % efficiency for throw in attacks* - Free kick shots - Goals free-kick attack - % scored free kick shots*- Penalties - Penalties scored - Penalties scored %*.
In possession positional (meters)*	- Building up defensive line height (IP-BU-DLH) - Building up in width (IP-BU-WIDTH) - Building up in length (IP-BU-LENGTH) - Building up area (m2) (IP-BU-CV) - Progression phase defensive line height (IP-PP-DLH) - Progression phase width (IP-PP-WIDTH) - Progression phase length (IP-PP-LENGTH) - Progression phase area (m2) (IP-PP-CV) - Final third phase defensive line height (IP-FTP-DLH) - Final third phase width (IP-FTP-WIDTH) - Final third phase length (IP-FTP-LENGH) - Final third phase area (m2) (IP-FTP-CV).
Out of possession positional (meters)*	- Low block defensive line height (OP-LB-DLH) - Low block width (OP-LB-WIDTH) - Low block length (OP-LB-LENGTH) - Low block area (m2) (OP-LB-CV) - Middle block defensive line height (OP-MD-DLH) - Middle block width (OP-MD-WIDTH) - Middle block length (OP-MD-LENGTH) - Middle block area (m2) (OP-MB-CV) - High block defensive line height (OP-HB-DLH) - High block width (OP-HB-WIDTH) - High block length (OP-HB-LENGT) - High block area (m2) (OP-HB-CV).

Note: *Indicators in absolute value.

This statistical procedure was chosen based on the central limit theorem due to the sample size for both groups (greater than 30 cases). To measure the magnitude of the difference between the two groups, Cohen's d statistics was used. Batterman and Hopkins (2006) defined this effect size as trivial (<0.20), small (0.20-0.60), moderate (0.60-1.20), large (1.20-2.0), very large (2.0-4.0), or extremely large (>4.0).

Once the variables that presented significant differences between the qualified and non-qualified teams were known, a binary logistic regression model was created. In this model, the classification variable was introduced as an explained variable and as explanatory variables, all those that presented significant differences from the Student's t-test for independent samples (p<.05). The possible collinearity problems were analysed and discarded from the matrix of correlations between the predictor variables. To create the final model, two previous preliminary models were carried out using the step-forward and step-backward methods in which variables were included and eliminated progressively from the Wald statistic with a level of

Table 2. Descriptive results of the variables that have presented significant results

	TOTAL N=128	QUALIFIED n=79	NON-QUALIFIED n=49	p [ES]
OP-HB-CV	1489.78±111.34	1455.86±96.99	1544.48±112.08	<.001 [0.80]
Norm free ball pick ups	1.94±.54	1.80±.51	2.17±.52	<.001 [0.69]
Norm yellow cards	0.06±0.067	0.051±0.056	0.0967±0.075	<.001 [0.67]
Accurate passes. %	84.39±4.77	85.60±4.43	82.44±4.71	<.001 [0.66]
OP-HB-WIDTH	40.60±2.08	40.10±2.04	41.40±1.92	<.001 [0.62]
OP-MB-Area	1079.85±119.54	1052.49±99.67	1123.98±135.82	<.005 [0.60]
Average possession time	17.96±4.87	19.03±5.32	16.24±3.44	<.001 [0.57]
Norm lost balls	2.42±.75	2.27±.73	2.68±.72	<.005 [0.56]
Effective playing time (min)	28.95±7.95	30.57±8.54	26.37±6.16	<.005 [0.53]
OP-HB-LENGTH	36.68±1.91	36.30±1.57	37.30±2.26	<.005 [0.52]
Norm ball possessions. quantity	3.59±.93	3.41±.94	3.89±.83	<.001 [0.51]
Norm free kick attacks	0.10±0.07	0.09±0.06	0.12±0.078	<.005 [.50]
Norm defensive challenges won	1.53±.56	1.43±.55	1.69±.54	<.05 [.46]
Norm challenges	5.73±1.78	5.43±1.75	6.23±1.73	<.05 [.44]
Norm challenges won	2.85±.88	2.70±.890	3.09±.831	<.05 [.44]
OP-MB-LENGTH	26.91±2.62	26.47±2.22	27.63±3.07	<.05 [.44]
Norm opponent´s xG	0.05±0.04	0.05±0.04	0.069±0.06	<.05 [.43]
Norm attacks left flank	0.93±0.24	0.8930±0.24	0.997±0.23107	<.05 [.43]
Norm attacks – center flank	0.72±0.23	0.69±0.20	0.79±0.25	<.05 [.43]
Norm counterattacks	0.44±0.22	0.40±0.21	0.50±0.24	<.05 [.43]
Norm defensive challenges	2.90±1.08	2.73±1.04	3.19±1.11	<.05 [.42]
Norm attacking challenges	2.82±.81	2.69±.80	3.03±.78	<.05 [.42]
Norm entrances to the opposition half	2.00±.39	1.93±.36	2.10±.43	<.05 [.42]
OP-MB-WIDTH	40.18±2.17	39.78±2.05	40.69±2.26	<.05 [.42]
Norm total actions	29.63±3.26	29.12±3.32	30.46±3.03	<.05 [.41]
Norm penalties	0.01±0.03	0.02±0.046	0.005±0.015	<.05 [.41]
Norm lost balls in own half	0.55±0.31	0.51±0.31	0.63±0.31	<.05 [.40]
Norm set pieces	0.29±0.12	0.27±0.11	0.32±0.13	<.05 [.39]
% efficiency for free kick attacks	31.98±34.64	37.13±36.27	23.67±30.38	<.05 [.39]
Norm penalties scored	0.01±0.02	0.0149±0.034	0.003±0.013	<.05 [.39]
IP-FTP-Area	1593.89±112.09	1576.95±104.11	1621.22±119.98	<.05 [.39]
IP-FTP-LENGTH	36.19±2.24	35.89±2.41	36.67±1.89	<.05 [.34]
% of efficiency for set piece attacks	23.33±21.64	33.15±20.77	24.46±15.04	<. 05 [0.20]

Note. Norm: normalised; OP-HB-AREA: out of possession, high block, area m^2; OP-HB-WIDTH: out of possession, high block, width; OP-MB-Area: out of possession, middle block, area; OP-HB-LENGTH: out of possession, high block, length; OP-MB-LENGTH: out of possession, middle block. length; OP-MB-WIDTH: out of possession, middle block, width; IP-FTP-AREA: in possession, final third phase, area; IP-FTP-LENGTH: in possession, final third phase, length.

significance p<.05. Finally, the step-forward method was selected for having greater predictive power.

All analyses were performed with SPSS 26.0 statistical software (IBM. Corp. Released 2017. IBM SPSS Statistics for Windows, Version 26, IBM Corp., Armonk, NY, USA).

Results

Descriptive and bivariate analysis

Table 2 presents descriptive and comparative results between the teams qualified for the round of 16 and those eliminated in the group phase, sorted by effect size. Statistically significant differences were observed for 33 out of the 123 indicators analysed. The results for all the variables analysed are presented in Appendix 1.

Binary logistic regression analysis

Table 3 presents the results obtained from the binary logistic regression technique. The regression model introduced 12 explanatory variables that influenced the probability of a team to be or not qualified for the round of 16 or later phase. It was possible to observe how norm air challenges won (OR = 51.574), % of efficiency for set piece attacks (OR= 1.145), norm free kick attacks with shot (OR= 4.132E+11), and % penalty scored (OR= 1.026), significantly increased the likelihood that the analysed team was one of the qualifiers for the round of 16. In relation to positional variables, it was discovered that when the team held possession in the final third, particularly with a higher defensive line (IP-FTP-DLH) (OR= .614), the team had an increased likelihood of advancing to the round of 16. Similarly, in the defensive phase, a higher length (OP-MB-LENGTH) of the mid-block team and a higher effective high-block playing space (OP-HB-CV) were variables that increased the odds (OR= 0,556 and 0,975 respectively) that the observed teams would be eliminated in the group phase.

Table 3. Multivariate results based on the explained variable qualified/non-qualified

Indicators in the equation						
	B	**S.E.**	**Wald**	**df**	**Sig.**	**Exp(B) [95% CI]**
Norm yellow cards	-23.731	7.383	10.332	1	.001	0.001 [0.000-0.001]
Norm Air Challenges Won	3.943	1.650	5.710	1	.017	51.574 [2.032-1309.06]
Norm free ball pick ups	-4.832	1.357	12.673	1	.000	0.008 [0.001 – 0.114]
Norm opponent´s xG per shot	-834.745	278.601	8.977	1	.003	0.001 [0.001-0.001]
Low pressing. %	-0.069	0.025	7.753	1	.005	0.933 [0.888-0.980]
Norm set piece attacks with shot	-23.764	9.401	6.390	1	.011	0.001 [0.000 – 0.005]
% of efficiency for set piece attacks	0.135	0.039	11.861	1	.001	1.145 [1.060-1.237]
Norm free kick attacks with shot	26.747	12.599	4.507	1	.034	4.132E+11 [7.794-2.190E+22]
% penaltis scored	0.026	0.013	4.179	1	.041	1.026 [1.001 – 1.052]
IP-FTP-DLH	0.488	0.222	4.827	1	.028	0.614 [0.397 – 0.949]
OP-MB-LENGTH	-0.587	0.208	8.011	1	.005	0.556 [0.370 – 0.835]
OP-HB-Area	-0.025	0.006	17.014	1	.000	0.975 [0.964 – 0.987]
Constant	92.437	25.479	13.162	1	.000	1.396E+40

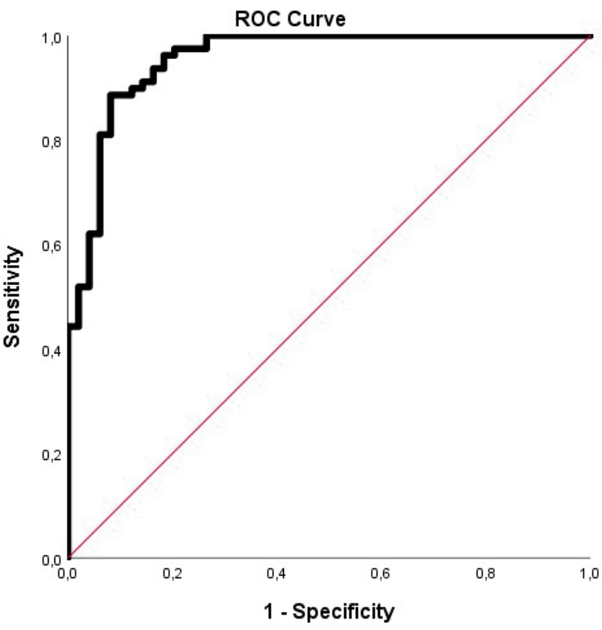

Figure 1. ROC curve for binary logistic regression model.

The fit of the model was evaluated and accepted from the Shapiro-Wilk normality contrast (p<.05) for the adjusted residuals. Likewise, the classification percentage of the model was 88.3% (89.9% sensitivity; 85.7% specificity; 84.0% negative predictive value; 91.02% positive predictive value; R2 Nagelkerge = .738). For its part, the receiver operating characteristic (ROC) curve is presented in Figure 1. The area under the curve (AUC*)* was .955 [95% C.I. = .919 - .991].

Discussion and conclusions

The aim of this study was to identify the technical-tactical indicators and collective positioning that differentiated between the teams qualified and the teams not qualified for the final phase of the FIFA World Cup Qatar 2022, considering effective playing time. Similarly, efforts have been made to understand the interaction of variables that significantly increased the likelihood of reaching the mentioned phase in the analysed championship, using a binary logistic regression model. To achieve this aim, we normalised the KPIs related to the technical-tactical actions carried out during the matches using the procedure proposed by Phatak et al. (2022). This allowed us to adjust the absolute values of each of the evaluated KPIs based on the minutes of effective playing time. The main findings of our study revealed significant differences between the qualified and non-qualified teams, specifically in relation to aerial challenges won, effectiveness in set-piece plays, and the offensive and defensive dispositions of the teams.

At the bivariate level, statistically significant differences were found between the qualified and non-qualified teams in many positional variables. Positional variables without ball possession OP-HB-Area (out of possession, high block, area m^2), OP-HB-Width (OP, high block, width), OP-MB-Area (OP, middle block, area m^2), OP-MB-LENGTH (OP, middle block, length), OP-MB-Width (OP, middle block, width) were significantly lower in the qualified teams. That is, the qualified teams pressured the possession of the rival team by further reducing the offensive effective playing space for them, compared to the non-qualified teams. These results corroborate those found in the works by Bauer and Anzer (2021), Casal, et al. (2016), Casal et al. (2021a), and Vogelbein et al. (2014) in which it is also indicated that the best teams perform pressure after the loss of ball possession more effectively, reducing the effective playing space of the rival team after losing possession of the ball. In the same way, it was found that the most effective recoveries were those of shorter duration, which would mean that performing pressure after loss is necessary.

In their work, Castellano et al. (2022) analysed the total distance covered and the speed of players during effective playing time and in relation to ball possession. The study concluded that the teams with the most ball possession time were those that travelled more meters above 21 km/h in the defensive phase (normalised distance >21 km/h high possession teams out of possession = 139.3±28.9; normalised distance >21 km/h low teams out of possession= 102.8 vs 23.7). This fact may indicate that the best teams perform defensive transitions at a higher speed than the bottom teams, quickly reducing effective playing space to rival teams.

On the other hand, moderate differences were found in positional variables of ball possession. Specifically, the qualified teams developed their ball possessions in the last rival third in smaller spaces (IP-FTP-DLH, IP-FTP-LENGTH) compared to the non-qualified teams. These results are in line with the work of Casal et al. (2017) in which it is also indicated that the best teams are characterized by longer ball possessions in areas close to the opponent's goal.

Regarding ball possession, significant differences have been found in the accurate passes %, average possession time and effective playing time in favor of the qualified teams and, on the contrary, the non-qualified teams have shown superior results in the variable norm free ball pick-ups, norm lost balls, norm ball possession quantity, and norm ball lost in the own half. This means that the qualified teams have been characterized by having a lower number of possessions because these are of longer duration, and with a greater number of passes. On the other hand, the non-qualified teams have had more losses in ball possession. These data match those provided by previous studies (Bradley, et al., 2014; Carling, et al., 2015; Casal, et al., 2017, 2021b; Collet, 2013; Liu, et al., 2016; Moura, et al., 2014) and can confirm a higher technical quality of the qualified teams compared to those non-qualified ones.

The non-qualified teams showed significant differences in favor of some defensive indicators, such as norm defensive challenges won, norm challenges, norm challenges won, and norm defensive challenges. These results indicate that the lower-ranking teams are characterized by performing a greater number of defensive actions rather than offensive ones, coinciding with the results of Casal et al. (2021b) and Delgado-Bordonau, Domenech-Monforte, Guzmán, and Mendez-Villanueva (2013), who indicate that these results can be explained by these teams remaining longer in the defensive phase than in the offensive one.

We have also been able to see how the non-qualified teams presented higher values in all types of attacks. We believe that this can be explained by the fact of presenting a greater number of actions and attacks. As for the set pieces, the qualified teams showed greater effectiveness in the set pieces and free kicks attacks, something that corroborates the findings found by Gouveia et al. (2022). These authors found that successful teams in Portugal were twice as likely to score corners compared to unsuccessful teams. Similarly, in the English Premier League it was found that the six bottom teams finished with a goal shot 7.1% of the corners executed compared to 7.8% efficiency of the top six teams (Strafford, Smith, North, & Stone, 2019). Regarding regulatory aspects, the results of this study demonstrated the existence of significant differences in the number of yellow cards normalised based on the effective playing time, in favor of the non-qualified teams (p<.001; ES = .67).

The multivariate analysis has made it possible to identify the indicators and positions that allow predicting the passage or not to the final phase of groups and, therefore, what were the key performance factors in this competition. Specifically, the air challenges won made it possible to increase the chances of qualifying for the next phase. De Jong, Gastin, Angelova, Bruce, and Dwyer (2020) already showed that the number of individual encounters won was a clear determinant of the success of football teams, which can indicate that collective performance can often be subject to individual performance in specific actions.

The indicators related to the effectiveness of set pieces (% efficiency for set piece attacks, free kick attacks with shot and % penalty scored) significantly increased the odds ratio in favor of the qualified teams, appearing as performance predictors. These findings are consistent with previous research that suggests that, although corner kicks (Casal, Maneiro, Ardá, Losada, & Rial, 2015; Casal, et al., 2016) and indirect free kicks (Casal, Maneiro, Ardá, Rial, & Losada, 2014; López, et al., 2018) have a relatively low success rate, they often play a crucial role in the outcomes of matches.

Furthermore, in relation to these indicators, it can be thought that the performance of a team in an international championship can be determined to a large extent by the degree of success in this type of static action, being the effectiveness in set pieces one of the main factors that can determine and differentiate performance among elite football teams. Therefore, currently what can determine the performance in high-level football is not only the collective tactical bahavior, which is presupposed very high and similar in all teams, but the individual or partially collective success of a team in the execution or defence of the set pieces.

The OP-MB-LENGTH and OP-HB-CV defensive positioning and the IP-FTP-DLH offensive positioning have also made it possible to predict the passing or not to the next competitive phase. Teams that adopted a more compact defensive formation, limiting the effective playing space available to the opponent, were more likely to qualify for the next phase. The defensive positions OP-MB-LENGTH and OP-HB-CV, as well as the offensive position IP-FTP-DLH, also enabled the prediction of whether the team would progress to the next competitive phase. Teams that maintained a more compact defensive formation, thereby reducing the effective playing space to the opponent, were more likely to qualify for the next phase. On the other hand, a higher defensive line height of the teams when in possession in the final third increased the likelihood of the teams progressing to the next phase. This is significant, as it may indicate a higher technical-tactical quality of the players in the qualified teams, allowing for the development of ball possessions in smaller spaces in depth, keeping the lines very close together, thereby facilitating pressure after losing possession in the discussed defensive transitions. In this sense, the evidence has previously shown that the best teams have a higher technical performance compared to the bottom teams (Castellano, et al., 2012; Harrop & Nevill, 2014; Winter & Pfeiffer, 2016), in the same way that can be contrasted in the results of our study. Concretely, pass accuracy was higher for the qualified teams (85.6 vs. 82.4) as was average possession time (19.03 vs. 16.24). In contrast, the number of lost balls per minute of effective playing time was lower across the field (2.27 vs. 2.68) and in the rival field (0,51 vs. 0.,0,6363), and the total number of possessions was lower (3.41 vs 3.89), indicating a higher quality in maintaining these possessions. Our results also corroborate those of previous studies indicating that the best teams are characterized by a higher percentage of possession time (Casal, et al., 2017; Hughes & Franks, 2005; Lago-Peñas & Dellal, 2010). Furthermore, by keeping the lines very close together and close to the rival goal, it allows greater effectiveness when making defensive transitions, being in numerical equality and drastically reducing the effective playing space to the rival team.

Finally, the number of yellow cards significantly influenced the proposed regression model, with a multivariate effect that decreased the odds ratio in favor of the qualified teams as the number of yellow cards increased. These findings are consistent with those of Fernández-Cortés, Gomez-Ruano, Mancha-Triguero, Ibáñez, and García-Rubio (2023) and Casal et al. (2021b) who observed that the number of cards received per match was higher in the bottom teams or in those who lost or tied their matches compared to the best teams or who were winners. Therefore, this seems to indicate that the best teams incur fewer anti-regulatory sanctions susceptible to reprimand, although it is true that the effective playing time in possession of the ball was greater for the qualified teams (30.57 ± 8.54 minutes vs. 26.37 ± 6.16) thus making them less predisposed to commit this type of actions.

This research study had some limitations that should be mentioned. First of all, while the FIFA World Cup is considered to be the most important competition at the national team level, the fact that the results obtained refer to a single edition means a reduction in the extrapolation of these results. In addition, during the development of a championship such as the one analysed, there may be various circumstances that allow different teams to advance through the eliminations due to random effects or specific actions. This fact can be a bias in the data analysed, being influenced to a large extent by the play models of those national teams that played more matches. Regarding the practical applications of this study, we have been able to identify tactical behaviors and positioning patterns that have made the difference between high-performing and low-performing teams, taking into account the effective playing time. This information can be highly valuable for coaches as it provides them with useful insights for designing training tasks aimed at replicating these behaviors. Additionally, it can have a strategic impact when selecting playing styles for teams.

In conclusion, we have been able to verify how we have obtained significant differences in 33 indicators out of the 137 analysed and of these, 12 indicators allowed us to differentiate, at a multivariate level, the performance between the qualified and non-qualified teams. This data shows the enormous equality that currently exists in high-level football where the effectiveness of set pieces can make the difference between the teams. The qualified teams were characterized by making longer possessions in the areas near the rival's goal, in very small playing spaces, keeping the lines very close together and with the defensive line very far ahead. These teams also made rapid defensive transitions, pushing and quickly reducing the playing space of rival teams as soon as they lost possession of the ball.

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Appendix 1. Operational definitions of the variables analysed.

VARIABLE	OPERATIONAL DEFINITINION
Goals	A shot on target that leads to a ball fully crossing the goal line.
Chances	A goal-scoring opportunity, when the attacking team gets a clear-cut chance to score a goal.
Chances successful	A goal-scoring opportunity that was converted into a goal; may not be equal to the number of goals, as some goals are own goals or rebounds happened during ball possession transition.
Chances successful %	Percentage share of chances successful in the total number of chances. This parameter is generated automatically.
Fouls	Action that impedes the progress and success of the opposing team and obtaining an advantage by breaking the rules of the game.
Yellow cards	A cautionary directive illustrated by a yellow card from the referee for a moderate to serious foul or penalty.
Red cards	An expulsion from the field for the most serious of fouls such as violent contact. blatant breaking of rules to avoid an opponent goal or a second yellow card.
Offsides	A player is in an offside position if: any part of the head, body or feet is in the opponents' half (excluding the halfway line) and any part of the head, body or feet is nearer to the opponents' goal line than both the ball or the second-last opponent.
Corners	Awarded after a ball being sent across the sideline of the own half of the field by a defending team player.
Corner attacks with shots	A corner finished with a shot.
Efficiency corner. %	Percentage of corners finished with a shot.
Total actions	Total number of all types of passes (including crosses and set pieces passes). challenges, interceptions, picking up free balls, dribbling, bad ball controls and all kinds of shots (including goals), shots saved and goals conceded. Fouls are not included in total actions.
Successful actions	Successfully completed actions out of total actions.
Successful actions %	Percentage share of successfully completed actions in total actions.
Shots	Total number of all shots made during the course of a game; includes shots on target. shots wide, blocked shots and shots on post / bar.
Shots on target	Shots going inside the goal, might end in a goal or be deflected by the goalkeeper or by a field player from the GK zone.
Shots on target. %	Percentage share of shots on target in the total number of shots.
Passes	An attempt to transfer a ball from one teammate to another with the purpose of attack build-up or keeping the possession.
Accurate passes perc	Percentage share of accurate passes in the total number of passes.
Key passes	A pass to a partner who is in a goal scoring position (one-on-one situation. empty net etc.) or a pass to a partner that "cuts off" the whole defensive line of the opponent's team (3 and more players) in the attacking phase.
Key passes accurate	Successful attempt of a key pass, when a teammate touches a ball; if a challenge was registered after a key pass, this pass is still considered as a "key pass accurate".
Crosses	A pass into the box from the flanks in the opponent's half of the field; strong and directed pass. It can be performed both in the air and on the ground, and it cannot be an action performed from a set piece.
Accurate crosses %	Percentage share of successful crosses in the total number of crosses.
Challenges	The summary type of a parameter, includes duels for the neutral balls, air duels for the neutral balls, dribbles, tackles and losing the ball during opponent tackling attempts; the total amount of attacking and defensive challenges.
Challenges won	Successful challenge is registered for a player of a team that keeps possession of a ball after such challenge; lost challenge is simultaneously registered for a player's opponent.
Challenges won. %	Percentage share of challenges won in the total number of challenges.
Defensive challenges	Challenges involving a player of the team that does not currently possess the ball; the number of defensive challenges of the team is always equal to the number of attacking challenges of their opponents.
Defensive challenges won	Successful attempts of defensive challenges that lead to a touch made by own team player.
Challenges in defence won. %	Percentage share of defensive challenges won in the total number of challenges.
Attacking challenges	Challenges involving a player of the team that currently possesses the ball.

Attacking challenges won	Successful attempts of attacking challenges that lead to the ball remaining in possession of own team.
Attacking challenges won. %	Percentage share of attacking challenges won in the total number of challenges.
Air challenges	Two players of the opposing teams challenging for the ball in the air, at least above shoulder height, the rivals play or try to play with their heads.
Air challenges won	Successful attempt of air challenge that leads to a touch made by own team player.
Air challenges won. %	Percentage share of air challenges won in the total number of air challenges.
Dribbles	Is an active action performed by a player in order to get through an opponent; can be performed as a trick or fake movement, as a ball poked at speed, no-touch ball etc
Dribbles successful	Successful attempt of a dribble. as a result a player committing a dribble always keeps the ball and improves his position, leaving the opponent behind.
Successful dribbles. %	Percentage share of successful dribbles in the total number of dribbles.
Tackles	This parameter is registered automatically for own team player in case an opponent is making a dribbling attempt; successful or unsuccessful tackle depends on the success of a dribble.
Tackles successful	Successful attempt of a tackle, as a result an opponent's player loses the ball while performing a dribble.
Tackles successful. %	Percentage share of successful tackles in the total number of tackles.
Ball interceptions	Player's active, targeted and successful action to either prevent a potentially accurate pass or to change the ball trajectory.
Free ball pickups	Recovering a neutral ball after an opponent lost it.
Lost balls	It is registered when a player loses the ball by a poor trapping of the ball, errant pass, unsuccessful attempt to shoot or an unsuccessful drible.
Lost balls own half	Lost balls occurred in team's own half of the pitch.
Ball recoveries	First player's action in a team's ball possession after the team started possessing the ball, except for the cases when Ball Possession starts from a set piece (including a throw-in).
Ball recoveries opponents half	Ball recoveries occurred in team's opponent's half of the pitch.
Total duration of ball possession	Sum of all time periods between the start of possession to the moment of transition, from the moment of transition to the moment of the next transition, from the moment of transition to the end of possession, as well as from the start to the end of possession in those cases when there was no moment of transition, e.g., if a ball went out.
Ball possessions (quantity)	Total number of periods of play from the start to the end of possession, even if the moment of transition was not registered.
Avg. duration ball possessions	Average period of time in which a team possessed a ball during the course of a match. It is calculated as the total duration of ball possession divided by the quantity of ball possessions.
Entrances opponents half	Number of team possessions during which at least one entrance into the opponent's half was made. Entrance is counted in as a result of one of the following actions: pass, challenge, tackle, dribble, ball recovery, ball loss, foul, YC, RC, all kinds of shots, interception, free ball pick up, GK interception, cross.
Entrances final third	Number of team possessions during which at least one entrance into the opponent's final third was made.
Entrances opponents box	Number of team possessions during which at least one entrance into the opponent's penalty box was made.
Positional attacks	All attacks from the open play that do not fit into counter attacks.
Positional attacks with shots	Positional attacks included at least one shot of any type from the attacking side.
Efficiency positional attacks	Percentage share of positional attacks with a shot in the total number of positional attacks.
Counterattacks	Attack from the open play that starts with winning the ball from a defensive position and then quickly transitioning to offense while the prior attacking team is caught in an offensive formation; the length of possession during the attack cannot exceed 8 seconds before the possession transition or end; alternatively the length of possession can last between 8 and 30 sec., but the speed of attack cannot be less than 2.6 m/s. A counterattack cannot begin with a pass from a goalkeeper if he controlled the ball for more than 4 seconds before the action.
Counterattacks with shot	Counter-attacks that included at least one shot of any type from the attacking side.
Efficiency counter attacks	Percentage share of counter-attacks with a shot in the total number of counter-attacks.
Set pieces attacks	Total number of free-kick attacks, corner attacks. throw-in attacks and penalties.
Set piece with shot	Set-piece attacks that included at least one shot of any type from the attacking side.

Efficiency set piece attack	Percentage share of set-piece attacks with a shot in the total number of counter-attacks.
Attacks left flank	Attacks occurred on the width of 20 meters from the left sideline, whole length of the sideline is considered; the attack is determined by the last action of an attack which isn't a shot or a goal and which didn't occur inside the penalty area.
Attacks shots left flank	Left-side attacks that included at least one shot of any type from the attacking side.
Efficiency attacks left flank	Percentage share of left-side attacks with shots in the total number of left-side attacks.
Attacks center	Attacks occurred between the space of left-side and right-side attacks, or central zone; the attack is determined by the last action of an attack which isn't a shot or a goal and which didn't occur inside the penalty area; determined for positional attacks and counter-attacks only.
Attacks with shots center	Central zone attacks included at least one shot of any type from the attacking side.
Efficiency attacks central zone	Percentage share of central zone attacks with shots in the total number of central zone attacks.
Attacks right flank	Attacks occurred on the width of 20 meters from the right sideline, whole length of the sideline is considered; the attack is determined by the last action of an attack which isn't a shot or a goal and which didn't occur inside the penalty area; determined for positional attacks and counter-attacks only.
Attacks with shots right flank	Right-side attacks included at least one shot of any type from the attacking side.
Efficiency attacks right flank	Percentage share of right-side attacks with shots in the total number of right-side attacks.

Appendix 2. Results of the analysed variables.

	TOTAL n=128	QUALIFIED n=79	NON-QUALIFIED n=49	p [ES]
OP-HB-CV	1489.78±111.34	1455.86±96.99	1544.48±112.08	<.001 [.80]
Norm free ball pick ups	1.94±.54	1.80±.51	2.17±.52	<.001 [.69]
Norm yellow cards	0.06±.067	0.051±.056	0.0967±.075	<.001 [.67]
Accurate passes. %	84.39±4.77	85.60±4.43	82.44±4.71	<.001 [.66]
OP-HB-WIDTH	40.60±2.08	40.10±2.04	41.40±1.92	<.001 [.62]
OP-MB-CV	1079.85±119.54	1052.49±99.67	1123.98±135.82	<.005 [.60]
Average possession time	17.96±4.87	19.03±5.32	16.24±3.44	<.001 [.57]
Norm lost balls	2.42±.75	2.27±.73	2.68±.72	<.005 [.56]
Effective playing time (min.)	28.95±7.95	30.57±8.54	26.37±6.16	<.005 [.53]
OP-HB-LENGTH	36.68±1.91	36.30±1.57	37.30±2.26	<.005 [.52]
Norm ball possessions. quantity	3.59±.93	3.41±.94	3.89±.83	<.001 [.51]
Norm free kick attacks	0.10±.07	0.09±.06	0.12±.078	<.005 [.50]
Norm defensive challenges won	1.53±.56	1.43±.55	1.69±.54	<.05 [.46]
Norm challenges	5.73±1.78	5.43±1.75	6.23±1.73	<.05 [.44]
Norm challenges won	2.85±.88	2.70±.890	3.09±.831	<.05 [.44]
OP-MB-LENGTH	26.91±2.62	26.47±2.22	27.63±3.07	<.05 [.44]
Norm opponent's xG	0.05±.04	0.05±.04	0.069±.06	<.05 [.43]
Norm attacks left flank	0.93±.24	0.8930±.24	0.997±.23107	<.05 [.43]
Norm attacks – center flank	0.72±.23	0.69±.20	0.79±.25	<.05 [.43]
Norm counterattacks	0.44±.22	0.40±.21	0.50±.24	<.05 [.43]
Norm defensive challenges	2.90±1.08	2.73±1.04	3.19±1.11	<.05 [.42]
Norm attacking challenges	2.82±.81	2.69±.80	3.03±.78	<.05 [.42]
Norm entrances to the opposition half	2.00±.39	1.93±.36	2.10±.43	<.05 [.42]
OP-MB-WIDTH	40.18±2.17	39.78±2.05	40.69±2.26	<.05 [.42]
Norm total actions	29.63±3.26	29.12±3.32	30.46±3.03	<.05 [.41]
Norm penalties	0.01±0.03	0.02±0.046	0.005±0.015	<.05 [.41]
Norm lost balls in the own half	0.55±.31	0.51±.31	0.63±.31	<.05 [.40]
Norm set pieces	0.29±.12	0.27±.11	0.32±.13	<.05 [.39]
% efficiency for free kick attacks	31.98±34.64	37.13±36.27	23.67±30.38	<.05 [.39]
Norm penalties scored	0.01±.02	0.0149±.034	0.003±.013	<.05 [.39]
IP-FTP-CV	1593.89±112.09	1576.95±104.11	1621.22±119.98	<.05 [.39]
IP-FTP-LENGTH	36.19±2.24	35.89±2.41	36.67±1.89	<.05 [.34]
% of efficiency for set piece attacks	23.33±21.64	33.15±20.77	24.46±15.04	<. 05 [.20]
Norm goals	0.047±.044	0.0397±.045	0.056±.050	>.05
Norm chances	0.201±.081	0.190±.113	0.212±.108	>.05
Norm chances successful	23.262±1.664	23.132±1.859	23.392±1.469	>.05
Norm fouls	0.369±.168	0.376±.145	0.361±.193	>.05
Norm red cards	0.002±.005	0.001±.008	0.002±.008	>.05
Norm offsides	0.074±.073	0.065±.064	0.083±.083	>.05
Norm corners	0.152±.091	0.154±.088	0.149±.094	>.05
Norm successful action	29.794±2.679	30.463±3.036	29.124±3.321	>.05
Norm shots	.369±.168	.376±.145	.361±.193	>.05
Norm shots on target	0.143±0.091	0.154±0.092	0.132±0.089	>.05
Norm shots off target	0.130±0.080	0.126±0.072	0.134±0.088	>.05
Norm shots blocked	0.086±0.078	0.089±0.063	0.083±0.093	>.05
Norm passes	18.357±.128	18.418±1.123	18.2961.134	>.05

Norm key passes	0.246±0.152	0.251±0.147	0.241±0.154	>.05
Norm accurate key passes	0.121±0.095	0.124±0.094	0.118±0.096	>.05
Norm crosses	0.409±0.167	0.385±0.160	0.434±0.176	>.05
Norm accurate crosses	0.118±0.077	0.120±0.079	0.116±0.074	>.05
Norm challenges won %*	49.992±4.682	50.025±4.804	49.959±4.560	>.05
Norm defensive challenges	2.964±1.088	2.734±1.044	3.193±1.112	>.05
Norm defensive challenges won	1.561±.549	1.430±.555	1.692±.543	>.05
Norm defensive challenges won %*	53.230±6.807	52.848±6.974	53.612±6.689	>.05
Norm attacking challenges won	1.339±.409	1.404±.420	1.275±.431	>.05
Norm air challenges	1.465±.544	1.364±.617	1.566±.471	>.05
Norm air challenges won	0.730±0.294	0.689±0.338	0.770±0.250	>.05
Norm dribbles	0.963±0.338	0.917±0.325	10.009±0.329	>.05
Norm dribbles successful	0.575±0.220	0.551±0.209	0.599±0.232	>.05
Norm dribbles successful %*	59.660±10.02	59.911±10.115	59.408±10.94	>.05
Norm tackles	1.292±.599	1.204±.575	1.380±.623	>.05
Norm tackles successful	0.662±0.293	0.618±0.295	0.706±0.292	>.05
Tackles successful %*	52.722±10.93	52.506±10.36	52.939±11.50	>.05
Norm ball interceptions	1.915±.844	1.789±.940	2.041±.708	>.05
Norm xG	0.049±0.03	0.052±0.031	0.047±0.032	>.05
Norm opponent´s xG	0.059±0.048	0.049±0.041	0.069±0.056	>.05
Norm Net xG	0.041±0.041	0.034±0.034	0.048±0.048	>.05
Norm xPoints	0.042±0.031	0.047±0.031	0.038±0.030	>.05
Norm xGConversion	0.046±0.076	0.046±0.064	0.045±0.088	>.05
Norm xGperShot	0.005±0.003	0.005±0.003	0.005±0.003	>.05
Norm xGperGoal	0.022±0.023	0.024±0.022	0.020±0.025	>.05
Norm Entrances to final third	1.278±.325	1.255±.280	1.301±.369	>.05
Norm Entrances to penalty box	0.468±0.175	0.469±0.152	0.466±0.198	>.05
Norm Team pressing	0.725±0.368	0.672±0.302	0.777±0.425	>.05
Norm Team pressing successful	0.294±0.147	0.269±0.118	0.319±0.176	>.05
Pressing efficiency (%)	42.227±15.41	42.215±15.68	42.24±14.94	>.05
Norm Building-ups	1.324±.287	1.288±.256	1.361±.273	>.05
Norm Building-ups without pressing	0.625±0.172	0.625±0.168	.625±.176	>.05
Norm High pressing	0.335±0.195	0.307±0.167	.363±.223	>.05
Norm High pressing successful	0.157±0.108	0.146±0.091	.167±.124	>.05
High pressing (%)	46.716±19.05	48.392±18.18	45.041±21.93	>.05
Norm Low pressing	0.390±0.210	0.365±0.174	0.414±0.247	>.05
Norm Low pressing successful	0.138±0.079	0.124±0.075	0.152±0.083	>.05
Low pressing successful (%)	37.802±18.65	36.114±21.03	39.490±18.21	>.05
Norm Positional attacks	2.169±.344	2.109±.386	2.229±.383	>.05
Norm Positional Attacks with shots	0.186±0.095	0.197±0.088	0.175±0.103	>.05
Positional attacks efficiency (%)	8.817±4.662	9.633±4.374	8.000±4.950	>.05
Norm Counterattacks with shots	0.071±0.072	0.063±0.059	0.078±0.085	>.05
Counterattacks efficiency (%)	14.825±11.32	15.570±14.70	13.347±10.69	>.05
Norm Set pieces attacks with shots	0.084±0.061	0.088±0.058	0.080±0.065	>.05
Norm Attacks through left flank with shots	0.946±0.237	0.893±0.243	0.998±0.231	>.05
Norm Efficiency of Attacks through left flank (%)	9.175±6.608	10.127±6.955	8.224±6.440	>.05
Norm Attacks through center flank with shots	0.090±0.063	0.086±0.053	0.093±0.073	>.05

Efficiency in attacks through center flank (%)	12.262±8.30	12.810±7.76	11.714±8.83	>.05
Norm Attacks through right flank	0.939±0.287	0.932±0.281	0.945±0.292	>.05
Norm Attacks through right flank with shots	0.077±0.062	0.081±0.062	0.073±0.062	>.05
Efficiency in attacks through right flank (%)	8.452±6.410	9.025±6.316	7.878±6.350	>.05
Norm Throw in attacks	0.033±0.054	0.024±0.050	0.042±0.057	>.05
Norm Throw in attacks with shots	0.004±0.012	0.003±0.010	0.005±0.015	>.05
% efficiency for throw in attacks*	5.483±19.458	5.190±20.11	5.776±18.79	>.05
Norm Free kick shots	0.014±0.024	0.014±0.022	0.013±0.026	>.05
Norm Goals Free-kick attack	0.001±0.004	0.000±0.003	0.001±0.005	>.05
Building up defensive line height (IP-BU-DLH)	19.595±1.877	19.48±2.36	19.71±2.01	>.05
Building up width (IP-BU-WIDTH)	54.085±3.163	53.93±2.98	54.24±3.38	>.05
Building up length (IP-BU-LENGTH)	39.228±1.690	39.316±1.75	39.14±1.82	>.05
Building up area (m2) (IP-BU-CV)	2122.955±168.50	2122.12±166.96	2123.79±172.0	>.05
Progression Phase defensive line height (IP-PP-DLH)	40.305±2.872	40.35±3.215	40.26±2.53	>.05
Progression Phase width (IP-PP-WIDTH)	55.270±2.625	55.44±2.314	55.1±2.93	>.05
Progression Phase length (IP-PP-LENGTH)	32.000±2.198	32.92±2.129	33.08±1.73	>.05
Progression Phase area (m2) (IP-PP-CV)	1823.885±134.52	1823.65±118.034	1824.12±150.02	>.05
Final third phase defensive line height (IP-FTP-DLH)	53.185±2.404	53.48±2.630	52.89±2.18	>.05
Final third phase width (IP-FTP-WIDTH)	44.110±2.520	44.00±2.418	44.22±2.62	>.05
Low block Defensive Line Height (OP-LB-DLH)	17.740±2.476	17.81±2.282	17.67±2.67	>.05
Low block width (OP-LB-WIDTH)	35.755±2.107	35.60±2.103	35.91±2.11	>.05
Low block length (OP-LB-LENGTH)	27.970±3.802	27.50±24.869	26.44±3.736	>.05
Low block area (m2) (OP-LB-CV)	963.805±724.978	978.81±896.524	948.79±137.42	>.05
Middle block defensive line height (OP-MD-DLH)	37.573±1.710	37.456±1.38	37.69±1.98	>.05
High block defensive line height (OP-HB-DLH)	47.723±1.748	48.025±2.08	47.42±1.56	>.05

EFFECTS OF SHORT AND LONG INTER-SET REST ON MAXIMAL ISOKINETIC STRENGTH AT SLOW AND FAST ANGULAR VELOCITIES IN TRAINED YOUNG MALES AFTER EIGHT WEEKS OF RESISTANCE TRAINING

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Abstract:

Resistance training is a widely used method to enhance muscle strength, with acute program variables influencing muscle adaptations. This study focused on the often-neglected variable of inter-set rest interval duration and its impact on muscle strength gains. Existing literature presents conflicting findings, with some studies advocating for longer rest intervals, while the others show comparable strength increases with shorter rests. Methodological differences in prescription and sample groups contributed to these inconsistencies. This study investigated the effect of short and long inter-set rests on maximal isokinetic strength gains of the upper and lower extremities during slow and fast angular velocities after eight weeks of resistance training. The research involved 26 healthy strength-trained males (age=20±1 year, body mass=81.5±8.8 kg, body height=184.4±6.1 cm) randomly assigned to G1m (1-minute rest) or G3m (3-minute rest). The resistance training programs were matched for all acute program variables, emphasizing the rest interval as the primary difference. Isokinetic dynamometry pre- and post-training assessed knee and elbow extensor and flexor maximal strength at 60°/s and 120°/s. The training program consisted of seven exercises performed at 70% 1RM until muscle failure three times per week over eight weeks. The most important result was that G3m, in contrast to G1m, led to a higher increase in peak torque of the knee (p=.037) and elbow extensors (p=.007) as well as the elbow flexors (p=.045) at 60°/s. Furthermore, G3m and G1m similarly increased the peak torque of the knee and elbow extensors and flexors at 120°/s and of the knee flexors at 60°/s (p>.138). In conclusion, the study suggests that strength training with longer inter-set rest intervals may lead to similar strength gains as strength training with shorter inter-set rest intervals. Nonetheless, individuals who prioritize maximizing their strength gains are advised to utilize longer rest intervals. However, shorter rest intervals may still yield significant strength enhancements, particularly for those who are limited by time.

Keywords: *strength training, rest intervals, muscle strength, isokinetic dynamometry*

Introduction

Resistance training is commonly used to increase muscle strength. The proper manipulation of acute program variables can influence these muscle adaptations (American College of Sports Medicine, 2009; Longo, et al., 2022). However, the rest interval duration is a significant acute program variable that is often neglected when designing resistance training programs. Currently, there are only a limited number of studies that have looked at how different inter-set rest intervals affect muscle strength, and their findings are inconsistent.

Resistance training guidelines recommend inter-set rest of long (>2 min) rather than short (<1 min) duration to increase muscle strength (Hill-Haas, Bishop, Dawson, Goodman & Edge, 2007; Schoenfeld, Pope, et al., 2016; Schoenfeld, Wilson, Lowery & Krieger, 2016). However, some studies show similar strength increases regardless of the inter-set rest (Ahtiainen, Pakarinen, Alen, Kraemer & Häkkinen, 2005; Buresh, Berg & French, 2009; Fink, Schoenfeld, Kikuchi & Nakazato, 2017; MacInnis, McGlory, Gibala & Phillips, 2017), but others show higher strength increases when using short inter-set rests (Villanueva, Lane & Schroeder, 2015). Such inconsistencies could be due to differences in the prescription of training variables and sample groups. Regarding training variables, studies exclusively investigated different durations of short (20 seconds to 1 min) and long (80 seconds to 5 min) rest intervals (Ahtiainen, et al., 2005; Fink, et al., 2017; Hill-Haas, et al., 2007) and differed between conditions for relative load, proximity to muscle failure and volume load (Buresh, et al., 2009; Fink, et al., 2017; Schoenfeld, Pope, et al., 2016). Regarding sample groups, some studies investigated physically inactive elderly persons (Villanueva, et al., 2015) or resistance-untrained individuals (Buresh, et al., 2009; Fink, et al., 2017; Piirainen, et al., 2011).

Another difference in the experimental designs is evident in the various methods used to assess muscle strength. Previous studies have laid the groundwork by employing diverse approaches to measure strength, each with its unique advantages and limitations, ranging from direct 1RM measurements to formula-based estimations and isokinetic dynamometer assessments (Buresh, et al., 2009; De Salles, et al., 2016; Piirainen, et al., 2011). The advantage of utilizing an isokinetic dynamometer lies in its capacity to measure muscle performance across various angular velocities, offering a more nuanced and practical comprehension. Incorporating assessments at both slow and fast angular velocities and evaluating both the flexors and extensors in the upper and lower extremities contributes to a thorough evaluation of muscular strength. This approach extends and combines insights from previous studies, providing a more holistic understanding of muscular strength.

Thus, studies investigating the effects of inter-set rest on muscular strength should compare short versus long intervals, last at least eight weeks, and match conditions for relative load, proximity to muscular failure, and volume load in resistance-trained individuals.

Therefore, the present study aimed to investigate the effect of short (one minute) and long (three minutes) inter-set rest on maximal isokinetic strength gains of the upper and lower extremities during slow (60°/s) and fast (120°/s) angular velocities after eight weeks of resistance training in trained young males. We hypothesized that two almost identical resistance training programs, with the only difference being the rest interval duration between sets, should have a similar impact on strength gains of the upper and lower extremities in young trained men.

Methods

Participants

An *a priori* analysis of statistical power performed with the G*Power program (Germany, Duesseldorf, version 3.1.9.7), based on a two-way analysis of variance with repeated measures, determined a required sample size of 22 participants. The minimum practically significant standardized effect size was set at 0.25, with an alpha level of 0.05, a statistical power of 0.80, and a correlation between repeated measures of 0.7.

The final sample consisted of young, healthy, and physically active male individuals (N = 26). Inclusion criteria for participants were the following: minimal knowledge and experience in resistance training, general health with no existing neurological or musculoskeletal disorders, and absence of injury history (with "hidden" or residual pain symptoms) to the trunk, upper, and/or lower extremities. Participants' age, body mass, height, and training experience are presented in Table 1.

Table 1. The age, body mass, height, and strength training experience of participants in G1m and G3m

	G1m	G3m
Age (year)	20.3 ± 1.0	19.5 ± 0.7
Body mass (kg)	82 ± 9.9	81 ± 7.8
Height (cm)	185.3 ± 5.6	183.5 ± 6.7
Training experience (year)	3.7 ± 1.4	4.2 ± 1.9

All participants were familiarized with the research objectives and risks and then gave informed consent to participate in the experiment. The research fully complied with the Declaration of Helsinki, and the experimental protocol was approved by the Scientific and Ethical Committee of the Faculty of Kinesiology University of Zagreb. Participants were instructed not to take any medications, consume any dietary supplements, or engage in any other systematic training during the experiment.

Participants were randomly assigned (using the random number generator function in Microsoft Excel, i.e., "=RAND()") to two equally sized groups: (1) resistance training with short rest intervals of one minute (G1m; n = 14) and (2) resistance training with long rest intervals of three minutes (G3m; n = 14).

Study design

The experimental design lasted 10 weeks, with the first and last weeks dedicated to testing and the remaining eight weeks were for the training program implementation. All tests (the initial and final condition) were performed at the same time of day for each participant to avoid possible influences of circadian rhythm fluctuations on strength (Grgic, et al., 2019) in the Laboratory for Motor Control and Performance at the Faculty of Kinesiology, University of Zagreb. Participants were instructed not to perform strenuous exercise 48 hours prior to the measurements. Each participant was trained and familiarized with the measurement protocol prior to the initial testing.

The first tests were administered to all participants during the first week. They aimed to determine baseline anthropometric characteristics, maximum concentric strength of the dominant arm and leg on an isokinetic dynamometer, and 1RM for all exercises included in the training program. For the next eight weeks, participants completed the training program three times per week. Final testing was performed in week ten, 3-5 days after the last training session. During the last week, participants were instructed not to do any other exercises or intense activities that could affect the final research results.

Procedure

Maximal isokinetic strength

The maximum concentric strength (peak torque and peak torque normalized to body mass) of the extensor and flexor muscles of the knee and elbow was measured using an isokinetic dynamometer (System 4, Biodex Corporation, Shirley, New York, USA) at two angular velocities—first at 60°/s and then, after a one minute rest, at 120°/s.

Measurement of the maximum concentric strength of the knee extensors and flexors was preceded by a standardized warm-up program consisting of three minutes of light jogging, dynamic stretching of the front and back thigh muscles, and ten forward and ten reverse lunges with each leg.

After the warm-up, participants were secured with straps in the dynamometer seat. The adjustment of the seat backrest distance was made to accommodate the positioning of the lateral femoral condyle's axis of rotation, as an anatomical reference point, in line with the dynamometer head's axis of rotation. For each participant, the dynamometer arm pad was individually adjusted proximally to the lateral malleolus. The range of motion ranged from 90° knee flexion to 10° knee extension, where 0° corresponded to a complete knee extension. Adjustments related to the effect of gravity on the shin and foot were made by weighing at a knee angle of 30°.

After two submaximal knee extension and flexion trials, participants performed three maximal repetitions. All measurements were accompanied by loud verbal encouragement.

The maximum concentric strength of the elbow extensors and flexors was measured after a break of approximately 20 minutes. The participants underwent a standardized warm-up again, which included a three-minute run, dynamic stretching of the arm muscles, and unilateral flexion and extension of the elbow (10 repetitions for each arm) with an elastic band.

The dynamometer was set up according to the manufacturer's instructions. Specifically, participants sat in the dynamometer seat with their shoulders, pelvis, and the upper arm of their dominant hand secured with straps. A 30° lateral angle was established between the upper arm and the trunk, and the dynamometer head height was aligned with the elbow rotation axis. The participants grasped the dynamometer arm pad handle with a hammer grip and performed elbow extensions and flexions within the range of 10-130° at the elbow joint (where 0° represented a complete extension of the elbow) at angular velocities of 60°/s and 120°/s. After two trial submaximal attempts, participants performed three maximal elbow extensions and flexions with the dominant arm. Loud verbal encouragement was provided throughout all measurements.

Maximal dynamic strength (1RM)

Prior to the training intervention period, all participants underwent one-repetition maximum (1RM) testing for each exercise following the guidelines established by the National Strength and Conditioning Association (Haff, et al., 2016) to determine individual initial training loads for each exercise. All exercises were tested in a single session with the testing order mirroring the exercise sequence used during the training program, with a 5-minute rest interval between exercises.

Before testing, participants participated in a general warm-up, including a three-minute run with tasks and brief dynamic stretching. Then, a specific warm-up set for the targeted exercise was performed, consisting of five repetitions at 50% of the estimated 1RM, followed by 1-2 sets of 2-3 repetitions with a load approximately corresponding to 60-80% of the estimated 1RM. The weight was gradually increased in subsequent one-repetition sets until the participants were still capable of performing the concentric muscle action through the full range of motion. The obtained 1RM was considered to be the highest weight lifted with a proper technique. A 3-minute rest was allowed between each consecutive attempt. All 1RM values for each exercise were determined within five attempts. The average 1RM values for groups G1m and G3m are presented in Table 2.

All testing was supervised by the research team to ensure consensus on the successful execution of each attempt.

Training program

The resistance training program was designed following all the aforementioned recommenda-

Table 2. 1RM (kg) in G1m and G3m

Group	Incline leg press	EZ bar French press	Barbell bicep curl	Leg extension	Prone leg curl	Cable triceps extension	Dumbbell Scott curl
G1m	211.5 ± 40.3	28.9 ± 10.7	34.0 ± 5.5	87.7 ± 12.2	75.0 ± 14.4	46.9 ± 11.1	28.1 ± 8.8
G3m	226.2 ± 21.8	28.5 ± 6.9	35.8 ± 7.3	96.2 ± 15.0	82.3 ± 10.9	46.6 ± 8.9	27.7 ± 5.5

tions about training program variables, and most of them were matched between the conditions, except the number of sets, which was increased in G1m to match the volume load of G3m. Specifically, each training session consisted of seven exercises (multi-joint and single-joint, using free weights and/or a machine) performed in the same sequence. However, to eliminate the influence of exercise order on dependent variables, participants began each session with a different exercise (i.e., 1234567, 2345671, 3456712…).

Two exercises were selected for each tested muscle group, and they were performed in the following sequence: 1) incline leg press, 2) Barbell Bicep Curl, 3) EZ bar French press, 4) leg extension, 5) dumbbell Scott curl, 6) cable triceps extension, and 7) prone leg curl.

The program included a general standardized warm-up, consisting of a three-minute run with tasks, followed by a brief dynamic full-body stretching routine (using a wooden stick), and, before the working sets, a specific warm-up involving one 10-repetition set of each exercise at 30% 1RM. All exercises were directly supervised to ensure correct execution and technique.

Further, the training intensity was individualized and corresponded to 70% of 1RM in each exercise. All sets were performed to the point of momentary concentric muscle failure, i.e., till the moment when it was no longer possible to perform the next concentric repetition while maintaining proper technique (Zaroni, et al., 2019). The predetermined load allowed an average of 12 repetitions per set in both groups (range: 10-14 repetitions). Therefore, the weight was adjusted so that the repetitions remained in the pre-established range regardless of changes in 1RM. However, due to the longer rest intervals between sets, G3m participants were able to perform sets of all exercises using heavier weights than G1m ($p<.004$).

Furthermore, the volume load relative to 1RM, calculated as the number of sets × repetitions × %1RM (Scott, Duthie, Thornton & Dascombe, 2016), was progressively increased by one set per exercise after the second and fifth weeks in both groups. By calculating the volume load for each exercise after each training session, it was found that the volume load was higher for G3m compared with G1m due to lifting heavier weights (Faraji, Vatani & Arazi, 2011). Therefore, it was necessary to precisely equalize the volume load of G1m concerning G3m. This was achieved originally and uniquely by adding one set per exercise in group G1m to the last training of each week.

In the first two weeks, G3m performed three sets, whereas from the third to the fifth week, four sets were performed, and from the sixth to the eighth week, five sets were performed per exercise per week (Table 3). Specifically, participants completed 24 training sessions over a total of eight weeks, with G3m performing a total of 99 sets and G1m performing 106 sets for each of the exercises.

Repetition tempo was also controlled, with concentric and eccentric muscle actions lasting ~1.5 seconds each on average, resulting in a total repetition time of approximately three seconds. Therefore, the only acute program variable that was expected to make a difference between the training groups was the rest interval between sets. Group G1m strictly adhered to a one-minute rest interval between sets, while group G3m had a three-minute rest interval.

Statistical analysis

All statistical procedures were conducted using the Statistical Package for the Social Sciences (IBM Corp. Released 2016; IBM SPSS Statistics for Macintosh, Version 24.0. Armonk, NY: IBM Corp.) and spreadsheet software (Microsoft Corporation. (2018). Microsoft Excel. Retrieved from: https://office.microsoft.com/excel).

Means and standard deviations were calculated for all variables, and the normality of distributions was assessed using the Shapiro-Wilk's test. To determine whether the groups differed in baseline values of all the measured variables before the training program, t-tests for independent samples were performed.

Table 3. Training protocol for both experimental groups

	Week	Sets		Average repetitions × average weight (kg)						
				Incline leg press	Barbell bicep curl	EZ bar French press	Leg extension	Dumbbell Scott curl	Cable triceps extension	Prone leg curl
G1m	1-2	3	+1 each week	13 × 174	12 × 18	12 × 19	12 × 67	12 × 18	12 × 29	12 × 58
	3-5	4		12 × 215	12 × 23	12 × 24	12 × 81	13 × 20	12 × 32	12 × 60
	6-8	5		12 × 234	12 × 23	12 × 26	12 × 86	13 × 21	12 × 33	12 × 63
G3m	1-2	3		13 × 210	12 × 20	12 × 20	13 × 80	12 × 17	12 × 31	12 × 59
	3-5	4		12 × 241	12 × 22	12 × 23	12 × 92	12 × 19	12 × 35	12 × 68
	6-8	5		13 × 261	12 × 24	12 × 25	12 × 97	12 × 21	12 × 37	12 × 72

Training effects within experimental groups were assessed using a series of paired t-tests with Bonferroni correction. Treatment effects within groups were assessed using Cohen's effect size index (ES; the difference between the final and initial condition divided by the standard deviation of the initial condition). An effect size of 0.2 was considered small, 0.5 moderate, and 0.8 large (Cohen, 1988). Effects were also expressed as percent change (the difference between the final and initial condition divided by the initial condition and multiplied by 100).

Differences in the effects of the program with different rest intervals for all dependent variables were tested with a series of two-way repeated-measures analysis of variance (Split-plot ANOVA or Mixed Design ANOVA) with a within-subjects factor (time) and another between-subjects factor (groups).

Partial eta squared (η2) was used as a measure of effect size and was classified as small ($0.02 \leq \eta2 \leq 0.12$), medium ($0.13 \leq \eta2 \leq 0.25$), or large ($\eta2 \geq 0.26$). The level of statistical significance was set at $p<.05$.

Table 4. Peak torque (Nm) of knee and elbow extension and flexion at angular velocities of 60 and 120°/s in the pre- and post-training of experimental groups (G1m and G3m). Effect size (Cohen's d), percentage change (%), the statistical significance of within-group differences between the pre- and post-training, and the statistical significance of group × time interaction

PEAK TORQUE (Nm)				G1m			G3m			
				M ± SD	ES	%	M ± SD	ES	%	F (p)
KNEE	60 °/s	EXTENSION	Initial	204.18 ± 19.36	1.48	14.07	200.31 ± 40.72	**1.58***	32.06	4.88 **(0.037**)**
			Final	232.91 ± 43.44			264.53 ± 31.91			
		FLEXION	Initial	109.17 ± 18.24	**1.53***	25.59	118.06 ± 21.21	**1.75***	31.45	1.56 (0.223)
			Final	137.11 ± 22.01			155.19 ± 22.11			
	120 °/s	EXTENSION	Initial	164.38 ± 18.65	**1.26***	14.33	161.99 ± 20.37	**1.67***	21.03	1.31 (0.264)
			Final	187.95 ± 20.79			196.06 ± 30.02			
		FLEXION	Initial	92.92 ± 13.19	**1.74***	24.76	101.42 ± 19.62	**1.75***	33.94	2.36 (0.138)
			Final	115.93 ± 23.19			135.85 ± 22.71			
ELBOW	60 °/s	EXTENSION	Initial	69.12 ± 14.13	0.28	5.65	67.58 ± 11.13	**1.25***	20.62	8.85 **(0.007**)**
			Final	73.02 ± 17.87			81.52 ± 11.82			
		FLEXION	Initial	59.09 ± 13.31	0.03	0.76	51.25 ± 11.80	**0.54***	12.37	4.48 **(0.045**)**
			Final	59.54 ± 10.61			57.58 ± 14.18			
	120 °/s	EXTENSION	Initial	55.92 ± 13.04	**0.74***	17.27	56.82 ± 9.02	**1.21***	19.24	.23 (0.635)
			Final	65.57 ± 15.09			67.75 ± 12.61			
		FLEXION	Initial	49.06 ± 11.39	0.20	4.53	45.34 ± 11.55	**0.48***	12.15	1.31 (0.264)
			Final	63.89 ± 11.22			63.49 ± 10.24			

Note. **p<.05; *p<.025; bolded results are statistically significant; G1m = group with a one-minute rest interval; G3m group with a three-minute rest interval; M ± SD = mean and standard deviation; ES = effect size; % = percent change.

Table 5. Normalized peak torque (Nm) of knee and elbow extension and flexion at angular velocities of 60 and 120°/s in the pre- and post-training of experimental groups (G1m and G3m). Effect size (Cohen's d), percentage change (%), the statistical significance of within-group differences between the pre- and post-training, and the statistical significance of group × time interaction

NORMALIZED PEAK TORQUE (Nm/kg)				G1m			G3m			
				M ± SD	**ES**	**%**	**M ± SD**	**ES**	**%**	**F (p)**
KNEE	**60 °/s**	**EXTENSION**	Initial	2.56 ± 0.37	0.86	12.35	2.53 ± 0.31	**2.49***	30.33	3.97 (0.058)
			Final	2.87 ± 0.58			3.30 ± 0.37			
		FLEXION	Initial	1.36 ± 0.25	**1.37***	25.45	1.50 ± 0.22	**1.95***	28.52	0.64 (0.430)
			Final	1.71 ± 0.21			1.93 ± 0.28			
	120 °/s	**EXTENSION**	Initial	2.05 ± 0.32	**0.88***	13.72	2.06 ± 0.21	**1.89***	19.18	0.99 (0.331)
			Final	2.34 ± 0.34			2.46 ± 0.28			
		FLEXION	Initial	1.16 ± 0.18	**1.39***	22.06	1.29 ± 0.21	**1.92***	31.90	3.49 (0.074)
			Final	1.42 ± 0.21			1.70 ± 0.21			
ELBOW	**60 °/s**	**EXTENSION**	Initial	0.86 ± 0.19	0.22	4.87	0.86 ± 0.10	**1.58***	18.42	8.71 **(0.007**)**
			Final	0.91 ± 0.20			1.02 ± 0.12			
		FLEXION	Initial	0.74 ± 0.17	0.01	0.23	0.65 ± 0.10	**0.67***	10.86	3.85 (0.061)
			Final	0.74 ± 0.12			0.72 ± 0.11			
	120 °/s	**EXTENSION**	Initial	0.70 ± 0.17	**0.68***	16.54	0.72 ± 0.09	**1.38***	17.93	0.17 (0.676)
			Final	0.81 ± 0.19			0.85 ± 0.14			
		FLEXION	Initial	0.61 ± 0.15	0.20	4.69	57.34 ± 11.09	**0.55***	10.73	0.87 (0.362)
			Final	0.64 ± 0.11			0.64 ± 0.10			

Note: **p<.05; *p<.025; bolded results are statistically significant; G1m = group with a one-minute rest interval; G3m group with a three-minute rest interval; M ± SD = mean and standard deviation; ES = effect size; % = percent change.

Results

Out of all the participants involved in the study, 93% actively participated in all training sessions as well as pre- and post-testing assessments. Specifically, two participants dropped out of the experiment: one from group G1m due to illness and one from group G3m due to personal reasons. Thus, the total number of participants analyzed who completed the study was 26, with 13 participants in each group. The initial states of peak torque and normalized peak torque (p>.125), 1RM (p>.128), and the volume loads (p=.372) were similar between groups for all the exercises. All variables were normally distributed (p>.098).

Values of the maximum concentric muscle strength of the knee and elbow extensors and flexors on the isokinetic dynamometer at two angular velocities of 60 and 120°/s, expressed as peak torque

(Nm) and peak torque normalized to body mass (Nm/kg) in the initial and final conditions of the tested groups G1m and G3m, effect size (Cohen's d), percentage change, statistical significance of the within-group differences between the initial and final conditions and statistical significance of the changes between the initial and final conditions are presented in Tables 4 and 5.

Discussion and conclusions

This study investigated the effect of short (one minute) and long (three minutes) inter-set rests on maximal isokinetic strength gains of the upper and lower extremities during slow (60º/s) and fast (120º/s) angular velocities after eight weeks of resistance training in trained young males. The programs were matched in all acute program variables except for the inter-set rest interval duration.

The main finding of this study was that three instead of one minute of inter-set rest resulted in higher increases in peak torque of the knee and elbow extensors and elbow flexors at 60º/s. Furthermore, three minutes and one minute of inter-set rest seem to have similarly increased the peak torque of the knee and elbow extensors and flexors at 120º/s and of the knee flexors at 60º/s.

However, considering effect sizes and changes from an applied standpoint, it is important to emphasize that even though a clear increase in peak torques is observed in both groups, these increases are more pronounced in G3m in all conditions. Specifically, large effect sizes and percent changes were found in G3m (21-34%) compared to G1m (14-26%) during knee extension and flexion, and 12-20% versus 0-17% in G3m compared to G1m during elbow extension and flexion. Although statistically insignificant, it appears that participants in G3m experienced a greater increase in strength than those in G1m. One reason for this could be that, although both groups trained to muscle failure using the same relative load, 3-minute rest between sets allowed a higher rate of weight progression throughout the intervention. The increased workload in G3m is, therefore, a direct consequence of the longer rest interval duration, which resulted in a faster recuperation and the sustained upkeep of a higher training intensity compared to a shorter rest interval (Willardson, 2006).

The results of our study are in concordance with the results of the study by Bemben, Fetters, Bemben, Nabavi & Koh (2000), showing a similar trend in strength increase across various but not all muscle groups. However, they are also in line with previous studies showing that training with higher loads causes a greater increase in muscle strength than training with lower loads (Carvalho, et al., 2022). Furthermore, these results appear to follow a dose-response relationship where the highest loads produce the greatest strength-related benefits. Studies by Campos et al. (2002), Fatouros et al. (2005, 2006), Jenkins et al. (2016), Jessee et al. (2018), Kubo, Ikebukuro & Yata (2021), Lasevicius et al. (2018, 2022), and Schoenfeld et al. (2014) have found a greater increase in muscle strength with higher weights, in contrast to Barcelos et al. (2015), Hortobágyi, Tunnel, Moody, Beam & DeVita (2001), Lopes et al. (2017), Taaffe, Pruitt, Pyka, Guido & Marcus (1996), and Vincent et al. (2002), who found no differences in the effect of the magnitude of weight on the development of muscle strength.

The only differences between the groups in terms of peak torque and normalized peak torque gains were found in four out of sixteen conditions, favoring the longer rest interval between sets, especially at lower angular velocities, with the differences decreasing as angular velocity increased. One possible reason for this is that G3m, due to a longer rest interval, recovered more, and started the next set with higher external loads, which, according to the force-velocity relationship, resulted in slower muscle contractions which are specific to testing with lower angular velocities.

The results confirm the effectiveness of both resistance training programs in developing muscle strength. Training programs that maintain similarity across all variables except for the duration of inter-set rest intervals demonstrate similar effects on the mechanical properties of muscles, regardless of body size. Therefore, the recommendation to use longer rest intervals in strength training for muscle strength development is questionable, given that shorter rest intervals can be just as effective as programs with longer rest intervals. Furthermore, results suggest that irrespective of training volume, the greatest influence on muscle strength enhancement is attributed to the magnitude of the training load, specifically the intensity. This can enhance the number of activated motor units, cause higher motor unit activation frequency, and greater changes in agonist-antagonist coactivation rate in comparison to lower intensities (Walker, 2021).

To summarize, the duration of rest intervals in resistance training programs does not have a significant impact on the development of muscle strength. Such generalizations should, however, be approached with caution. Although there were no statistically significant differences between the two groups of participants, a noticeable trend of greater increases was evident in the group with a longer rest interval for all the measured variables.

The changes that were observed can be practically applied, confirming their authenticity and observability. When examining the impact of rest interval duration on the peak torque and normalized peak torque, it is clear that a three-minute rest interval results in higher outcomes with greater effects and changes compared to a one-minute rest interval. Therefore, for individuals seeking to maximize muscle strength gains during resistance training, consider employing rest intervals of at least three minutes between sets. This duration proved effective in sustaining higher performance during the training session and contributed to notable increases in strength.

Based on the findings, it can be inferred that the acute program variables play a vital role in enhancing muscle strength. The changes that occur due to training are largely dependent on the specific training regimen, primarily in terms of training volume and intensity. While rest intervals play a role, prioritize training volume and intensity in resistance programs. Heavier weights have a direct correlation with increased muscle strength, emphasizing the importance of load management in training protocols. However, strength gains can still be achieved even with relatively lighter weights. The extent to which these gains are sufficient for improving sports performance or daily activities depends on individual needs and capabilities.

Additionally, the results of the study suggest that rest interval duration plays a secondary but still important role in muscle strength development. Shorter rest intervals are a more time-efficient approach, making it easier for individuals with busy schedules to stick to a regular training plan. This is especially important as lack of time is a common obstacle for people who want to participate in various training programs.

It is important to point out several methodological aspects. Firstly, the study was conducted solely on young males, which means that the findings cannot be applied to other populations, such as women, older individuals, or those with significant resistance training experience. Secondly, the researchers did not take into account the dietary intake of the participants, which could have influenced the outcomes in various ways. However, the participants were instructed to maintain their usual dietary habits and avoid consuming any additional sources of energy throughout the entire research process. And thirdly, it is important to highlight that the participants' maximum strength was determined using an isokinetic dynamometer. The challenge is that in natural movements of the human body, the angular velocity varies throughout the range of joint motion. In natural movements, the muscles undergo a cycle of stretching and shortening where the eccentric stretching of the muscle-tendon unit is followed by concentric contraction and the angular velocity changes as the joint angle changes. Despite this, with familiarity with the specific measurement nuances, isokinetic dynamometry is a reliable and valid tool for assessing the maximum strength of the participants.

Future studies could benefit from examining different participant groups such as women, untrained individuals, elderly, or clinical populations. It would also be helpful to monitor their food intake. Additionally, analyzing the mean velocity of set repetitions could provide clarity on why longer inter-set rest intervals improve isokinetic strength, particularly at lower angular velocities. This could also help in assessing fatigue, i.e., recovery levels.

In conclusion, although no statistically significant differences were observed between the groups, the study results suggest that longer inter-set rest intervals may lead to greater strength gains. It is essential to recognize the significance of rest intervals when it comes to individualizing training based on personal goals and needs. For individuals seeking to maximize their strength gains, longer rest intervals are recommended to maintain higher intensity. Nonetheless, for individuals who are under time constraints, shorter rest intervals may still result in significant improvements in strength gains.

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IMPACT OF CARRYING HEAVY LOADS ON POSTURAL SWAY AND RELATIVE GROUND REACTION FORCES DURING QUIET STANCE IN INTERVENTION POLICE OFFICERS

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Abstract:

Although carrying heavy loads impacts gait characteristics in military personnel, less studies have examined whether a gradually load increase affects foot parameters during quiet standing in the different population of intervention police officers. Therefore, the main purpose of the study was to examine differences in postural sway and ground reaction force characteristics during a quiet stance while carrying progressively heavier equipment. Ninety-six elite intervention male police officers were assessed under four conditions: (i) ‘no load’, (ii) ‘a 5 kg load’, (iii) ‘a 25 kg load’, and (iv) ‘a 45 kg load’. Foot characteristics during standing were assessed with the Zebris pedobarographic pressure platform. Heavier loads increased 95% confidence ellipse area ($p=.012$, $\eta2=0.028$), the center of pressure path length ($p=.010$, $\eta2=0.029$) and average velocity ($p=.011$, $\eta2=0.029$), and length of the minor ($p<.001$, $\eta2=0.040$) and major axis ($p=.004$, $\eta2=0.035$). No significant changes in relative ground reaction forces beneath the forefoot and hindfoot regions of both feet were observed ($p>.05$). The findings suggest that spatial and temporal foot parameters may be more prone to change while carrying heavy loads, especially the center of pressure characteristics.

Keywords: *special population, foot characteristics, center of pressure, statics, equipment, changes*

Introduction

Carrying excessive load represents a major part of both training and operation protocols in special population of military and police personnel (Brushøj, et al., 2008; Knapik, Reynolds & Harman, 2004; Wills, Saxby, Lenton & Doyle, 2021). Although such load is important for combat missions and specific tasks, it has been shown that it impacts optimal locomotor functions, increases the risk of lower limb injury (Wills, et al., 2021), and hampers physical performance (Boffey, et al., 2019; Martin, Kearney, Nestrowitz, Burke & Sax van der Weyden, 2023). Unfortunately, a negative trend in load weight has been observed, surpassing the recommended level of 45% of body mass (Andersen, Grimshaw, Kelso & Bentley, 2016; Orr, Coyle, Johnston & Pope, 2015). From a relative perspective, evidence shows that the load necessary for meeting tactical requirements ranges between 46% and 70% of body weight (Department of the Army, 2017).

When carrying heavy loads, an individual often tends to compensate, causing changes in gait and posture characteristics (Fox, Judge, Dickin & Wang, 2020). From a biomechanical point of view, heavy equipment during walking may impact balance, movement and overall postural stability, leading to greater torques in hip and trunk areas, which can cause alterations in body control (Heller, Challis & Sharkey, 2009). However, little evidence has been provided regarding carrying heavy loads and foot stability during quiet stance (Kasović, Vespalec & Štefan,, 2022; Richmond, Fling, Lee & Peterson 2021; Schiffman, Bensel, Hasselquist, Gregorczyk & Piscitelle , 2006; Walsh & Low, 2021;). In the process of quantifying the effects of load carriage in a stance position, first changed activity of anti-gravity muscles of the trunk should be observed, then, the postural sway as well as spatial- and temporal-related foot parameters, which may lead to higher incidence of injuries (Kroemer & Grandjean, 1997). The importance of establishing changes in biomechanical foot parameters in police officers during stance comes from a high prevalence of standing and less moving activities due to sitting in a patrol car or doing administrative tasks for a long period of time, which may lead to sedentarism (Orr, Hinton, Wilson, Pope & Dawes, 2020). The ability of standing still and remaining postural control while carrying heavy loads is important for balance control of the body, where heavier loads tend to trigger appropriate motor responses to avoid its loss or injury/fall (Pollock, Durward, Rowe & Paul, 2000). Even though a standing position seems relatively safe, an external load placement and the magnitude of an increased postural sway and a decreased base of support (considering feet together) represents one of the main problems causing muscle strains and negative body adaptations (Zultowski & Aruin, 2008). Although external load is important for survival, it may increase the risk of injury due to requirements to repetitively generate muscular force, causing whole-body fatigue and increasing energy costs connected to prolonged load carriage (Fallowfield, Blacker, Willems, Davey & Layden, 2012; Tahmasebi, Karimi, Satvati, & Fatoye, 2015). Indeed, evidence suggests that deviations of the center of pressure can predict future risk of injury and postural instability through shorter intervals in mediolateral axis (Blacker, Fallowfield, Bilzon & Willems, 2010), causing ligamentous damage, especially in the lower extremities (Knapik, et al., 2004). Both cross-sectional (Reynolds, White, Knapik, Witt & Amoroso, 1999) and longitudinal (Orr, et al., 2015; Orr, Coyle, Johnston & Pope, 2017) studies have shown that different load distribution may have even larger negative effects and can increase the level of asymmetry. Studies conducted during quiet standing have concluded that loads with a predominant mass of >40% of body weight increase pressure velocity and the contact area between the foot and the ground, directly affecting ground reaction forces beneath different foot regions (Kasović, et al., 2022; Richmond, et al., 2021; Schiffman, et al., 2006; Strube, et al., 2017; Tahmasebi, et al., 2015; Walsh & Low, 2021).

Although carrying heavy loads has been mainly observed in military personnel (Walsh & Low, 2021), studies have shown that other special populations, like police officers, may be more prone to biomechanical foot changes during quiet stance (Kasović, et al., 2022). Intervention police officers are required to perform their everyday tasks at a maximal level (Zwingmann, Zedler, Kurzner, Wahl & Goldmann, 2021). Their primary role includes intervening against crime and they are engaged in high-risk situations that often exceed the capabilities of general police (Zwingmann, et al., 2021). The most common everyday tasks are related to personal or community protection of high risk, including sports matches and events, rural operations of controlling an illegal border crossing by immigrants, or even participating in counter-terrorism operations (Irving, Orr & Pope , 2019). To be able to perform at high level, intervention police officers often need to carry external loads that exceed recommended levels of 45% of body mass (Department of the Army, 2017). Since intervention police officers may carry even heavier load than military personnel and engage in more high-risk situations (Zwingmann, et al., 2021), it is necessary to examine changes in biomechanical foot parameters during quiet standing under heavy load conditions.

Therefore, the main purpose of the study was to examine whether carrying progressively heavier loads (‘no load’, ‘a 5 kg load’, ‘a 25 kg load’, and ‘a 45 kg load’) had effects on postural sway and relative ground reaction forces during quiet stance in intervention police officers. We hypothesized that officers would exhibit greater biomechanical foot changes and impaired balance under heavier loads compared to the ‘no load’ condition.

Methods

Study participants

In this cross-sectional study, male officers of the Police Intervention Unit of the Zagreb Police Department were recruited. Out of 280 registered intervention police officers, we were able to recruit just 96 of them due to different field-based and administrative tasks other individuals were participating in. G*Power statistical calculator was used to calculate the effect size using partial eta squared and the one-way repeated-measures ANOVA to compare the effects of load configuration, with a p-value of <.05, achieved power of 0.80, a total recruited sample size of N = 80 (out of 280 participants), four measurements, correlation among repeated measures to be set at $r = 0.50$, and a nonsphericity correction index of 1, the achieved effect size with the aforementioned number of participants was f = 0.25. Considering the potential dispersion of the sample during the study, the initial sample size of 80 participants was increased by 20%, leading to the final sample of 96 participants. All participants in the research were employees of the Zagreb Police Intervention Unit for at least three years. All participants recruited for this study were men. Sociodemographic characteristics included age (mean ± SD; 38.2 ± 10.4 years), body height (179.2 ± 12.4 cm), body mass (86.4 ± 11.3 kg), body mass index (26.9 ± 3.8 kg/m^2), and waist circumference (93.5 ± 12.6 cm). The mean age of serving as an intervention police officer was 10.3 ± 3.3 years. Out of 96 participants, seven were underweight (7.3%), 65 had normal weight (67.7%), 20 were overweight (20.8%), and four were obese (4.2%). All participants signed a written informed consent to participate and stated that they did not have any acute/chronic diseases or injuries that would affect the test results or force them to drop-out from the study. The research was conducted anonymously and in accordance with the Helsinki Declaration (World Medical Association, 2013). This study was approved by the Ethical Committee of the Faculty of Kinesiology and the Police Intervention Department under the Ministry of Internal Affairs of the Republic of Croatia (Ethical code: 511-01-128-23-1).

Loading conditions

During testing, each participant walked over a platform and carried four types of loads proposed by the Ministry of Internal Affairs for intervention police officers: (1) body weight only ('no load'), (2) a 5-kg load ('load 1', a belt with a pistol loaded with a full handgun's magazine, an additional full handgun's magazine and handcuffs), (3) a 25-kg load ('load 2'; 'load 1' upgraded by a helmet, a ballistic vest and a multipurpose baton), and (4) a 45-kg load ('load 3'; 'load 2' upgraded by the additional protection for the lower extremities and a protective gas mask). The order of the load carrying was randomized by the randomization software to reduce the impact of a learning effect (Kasović, et al., 2022). All the participants wore the same standardized equipment for each load condition. Of note, each participant wore the handgun on the dominant side of the body, which was predominantly the right side (93% of all the participants).

Static foot parameters

Measurements were conducted at the same time in the evening hours and at the same place. All respondents were familiar with the measurement protocol before the measurements. First, the anthropometric characteristics of the examinees were measured, including body height and body mass. Ground reaction forces (absolute in N and relative in %) were measured. Each participant stepped barefoot on the Zebris medical platform for the measuring of pedobarographic plantar characteristics (type FDM 1.5). The Zebris platform uses 11.264 micro sensors, arranged across the walking area, with a frequency of 300 Hz. It has been used as a diagnostic device for supporting several modes of operation, including static analysis while a participant is standing quietly (Gregory & Robertson, 2017). The Zebris platform was connected via USB cable to an external unit (laptop). The data were gathered in real time using WinFDM software for the extraction and calculation. Measurement values could be additionally exported in the form of text, picture, and video, while simultaneously comparing the data from both feet. The capacity sensor technology was based on the automatic calibration of every single sensor integrated into the platform. The task was to stand on the platform and maintain a calm position, with the arms relaxed close to the body and looking straight forward. After 15 seconds of measurement, the following parameters were generated: (i) 95% confidence ellipse area (mm^2), (ii) CoP path length (mm), (iii) CoP average velocity (mm/s), (iv) length of the minor axis, (v) length of the major axis (mm), (vi) deviation X, (vii) deviation Y, and (viii) the angle between Y and the major axis (°). For ground reaction forces, the software generated the data for the relative forces distributed under the forefoot and hindfoot regions of the foot, as well as for the total foot (%). Of note, the vertical component of the ground reaction forces was collected and analyzed as well.

Statistical analysis

Basic descriptive statistics are presented as mean and standard deviation (SD). The Kolmogorov-Smirnov test was used to assess the normality of the distribution. Pearson correlation coefficient was used to assess the level of connection between sociodemographic characteristics and changes under each load condition, to omit a potential mediation. One-way repeated-measures ANOVA was used to test the effects of load configuration ('no load', 'load 1', 'load 2' and 'load 3'). Where significant differences between load configurations were observed, a modified Bonferroni procedure was used. All statistical analyses were performed using SPSS v23.0 software (IBM, Armonk, NY, USA) with an alpha level set *a priori* at $p<.05$ to denote statistical significance.

Results

Of note, sociodemographic characteristics of the study participants were not significantly correlated to changes in stance characteristics following different load conditions ($r = 0.03 – 0.21$, $p>.05$), omitting potential mediation between a specific load condition and spatiotemporal stance changes.

Changes in static foot parameters under the different loading conditions are presented in Table 1. Significant main effects were observed for confidence ellipse area, center of pressure path length and average velocity, length of the minor and major axes and deviation X. A Bonferroni *post-hoc* analyses revealed significant differences between 'no load' and 'load 3'. Specifically, carrying 'load 3' produced significantly larger effects on the aforementioned static foot parameters compared to the 'no load' condition. Interestingly, when carrying 'load 1', the value in deviation X axis significantly decreased compared to the 'no load' condition. Insignificant main effects in other static foot

Table 1. Basic descriptive statistics and changes in static foot parameters under the different loading conditions in intervention police officers

Study variables	'No load'	'Load 1'	'Load 2'	'Load 3'	Main effect	
Static parameters	**Median (25^{th}-75^{th})**	**Median (25^{th}-75^{th})**	**Median (25^{th}-75^{th})**	**Median (25^{th}-75^{th})**	***F* (p-value)**	**η2**
Confidence ellipse area (mm^2)	107.5 (68-183.5)[c]	124.5 (77.5-253.8)	144.5 (98.3-215.8)	188.5 (98.8-297.5)	**3.672 (0.012)**	**0.028**
Center of pressure path length (mm)	76.0 (63.3-91.8)[c]	81.5 (63.0-107.8)	82.0 (70.0-101.0)	91.0 (71.3-114.5)	**3.801 (0.010)**	**0.029**
Center of pressure average velocity (mm/s)	8.0 (6.0-9.0)[c]	8.0 (6.0-11.0)	8.0 (7.0-11.0)	9.0 (7.0-11.0)	**3.778 (0.011)**	**0.029**
Length of the minor axis (mm)	7.4 (5.1-9.6)[a,c]	8.3 (6.2-12.2)	8.6 (6.3-11.3)	9.1 (7.2-12.1)	**5.259 (<0.001)**	**0.040**
Length of the major axis (mm)	18.6 (14.8-24.5)[c]	22.1 (16.1-27.7)	21.1 (17.6-27.0)	23.9 (18.8-32.3)	**4.550 (0.004)**	**0.035**
Angle btween Y and the major axis (°)*	75.0 (16.0)	75.7 (14.5)	74.9 (15.4)	72.1 (20.0)	0.868 (0.458)	0.007
Deviation X (mm)	18.9 (8.4-31.0)[a]	13.9 (3.8-23.5)	17.7 (9.5-27.3)	18.4 (8.8-27.6)	**2.698 (0.046)**	**0.021**
Deviation Y (mm)	4.8 (-4.0-10.4)	6.9 (-2.2-15.2)	9.1 (-0.7-19.4)	9.3 (-2.2-17.1)	0.141 (0.935)	0.001
Relative average force-left forefoot (%)	54.1 (5.7)	55.0 (6.6)	55.5 (6.8)	55.5 (8.3)	0.884 (0.449)	0.007
Relative average force-left hindfoot (%)	45.9 (5.7)	45.1 (6.6)	44.5 (6.8)	44.5 (8.3)	0.898 (0.442)	0.007
Relative average force-left total (%)	44.9 (9.6)	46.3 (9.1)	44.1 (8.6)	44.3 (7.3)	1.233 (0.297)	0.010
Relative average force-right forefoot (%)	51.2 (7.9)	51.4 (10.1)	50.8 (8.7)	51.0 (7.7)	0.079 (0.972)	0.001
Relative average force-right hindfoot (%)	48.8 (7.9)	48.0 (8.7)	49.2 (8.7)	49.0 (7.7)	0.354 (0.787)	0.003
Relative average force-right total (%)	55.2 (9.6)	53.7 (9.1)	56.0 (8.4)	55.7 (7.3)	1.318 (0.268)	0.010

Note. [a] denotes significant differences between 'no load' and 'load 1'; [b] denotes significant differences between 'no load' and 'load 2'; [c] denotes significant differences between 'no load' and 'load 3'; [d] denotes significant differences between 'load 1' and 'load 2'; [e] denotes significant differences between 'load 1' and 'load 3'; [f] denotes significant differences between 'load 2' and 'load 3'. p<.05.

parameters were observed, pointing out that heavier equipment did not significantly impact deviation Y and relative forces under forefoot and hindfoot regions of both feet (p>.05).

Discussion and conclusions

The main purpose of the study was to examine whether heavier equipment led to changes in postural sway and relative ground reaction forces during quiet stance in intervention police officers. The main findings of the study are: (i) with the increased mass, increases in the center of pressure path length, average velocity and lengths of the minor and major axes gradually increased, and (ii) no significant changes in relative ground reaction forces beneath the forefoot and hindfoot regions of the foot were observed irrespective of heavier loads. Based on the aforementioned findings, the hypothesis of spatiotemporal and kinetic static foot changes when carrying different load could be partially confirmed, where spatiotemporal parameters led to significant changes, while relative ground reaction forces remained unchanged.

To the best of authors' knowledge, this is one of the first studies that examined whether heavier loads might impact static foot parameters in intervention police officers. Previous evidence has confirmed that heavier loads may impact several foot characteristics during quiet stance, including increases in mean postural sway during a double stance, the center of pressure path length, average velocity and lengths of the minor and major axes with a decrease in the angle between Y and the major axis (Strube et al., 2017; Walsh & Low, 2021). Specifically, a study by Strube et al. (2017) showed that mean postural sway velocity during a double leg stance increased from 0.27°·s^{-1} to 0.34°·s^{-1} when carrying 'a 16.0-kg load' and to 0.52°·s^{-1} under the '20.5-kg load', indicating a linear velocity increase while carrying heavier loads. However, the pattern of our findings clearly indicated significant differences only between 'no load' and 'load 1'/'load 3', while no other differences were observed. Unfortunately, we performed the experiment with a relatively small sample of intervention police officers; a greater sample might have led to a greater heterogeneity between the study participants in terms of their different characteristics, the duration of the load application, or the sensitivity of the postural sway measurement techniques employed. The nature of Zebris platform applied in this study was focused on vertical component (axis) of collecting the data, while antero-posterior or medio-lateral directions could not be determined. Although limited data had a significant impact on generalizability of the findings, uneven effects of carrying heavier loads on postural sway may be explained by the fact that experienced intervention police officers participated in the study, whose body adaptations were more adequate compared to new recruits. This is in line with previous evidence, where heavy load carried by young adults led to a decrease in postural stability with significant effects on the center of pressure sway area and the center of pressure anterior-posterior excursion (Martin, et al., 2023). Interestingly, studies have shown that 'a 16-kg load' may represent a significant cut-off point and result in substantial alterations in postural control (Heller, et al., 2009; Schiffman, et al., 2006; Strube, et al., 2017), compared to lighter loads, which is not in line with our findings. The *post-hoc* analysis showed that compared to the 'no load', 'a 45-kg load' led to significant changes in postural sway, mainly in the center of pressure. Of many potential factors influencing body posture, muscle activation plays an important role in maintaining an upright body posture and controls the integration of sensory systems during quiet standing (Kodithuwakku Arachchige, et al., 2020). Also, load placement relative to the body's center of mass was found to influence the amount of postural sway (Rugelj & Sevšek, 2011); when the load was placed above the center of mass, the sway parameters increased (Qu & Nussbaum, 2009). Although we were unable to test different load distribution and its impact on foot characteristics during quiet standing, studies have shown that load re-distribution towards the hips is an essential part of reducing metabolic costs and increasing contributions of hip muscles to forward progression (Jones, Canham-Chervak, Canada, Mitchener & Moore, 2010; Kavounoudias, Gilhodes, Roll & Roll, 1999). Heavier loads lead to greater foot changes and body sway during standing, which directly disrupt the body's center of mass to shift from a stable to the boundaries of the base of support, expecting a loss of balance in medio-lateral and anterior-posterior directions essential to maintain an upright stance by using the ankle and the hip compensation movements (Schiffman, et al., 2006). Losing postural stability is based on a stable system of a kinetic chain between gravity, the base of support and the center of mass. When an upright neutral position is impacted by external load, the resulting body motion is counterbalanced by one of the strategies which increases postural sway. Beside biomechanical, the physiological effects of carrying heavy loads often result in larger heart rate frequency, respiratory changes and proprioceptive systems (Horak & Nashner, 1986).

Along with postural changes, we observed no effects of carrying load on relative ground reaction forces, which is not in line with previous findings (Birrell, Hooper & Haslam, 2007; Kasović, et al., 2022; Walsh & Low, 2021). A study by Walsh and Low (2021) concluded that ground reaction forces linearly increased with heavier load. On the other hand, observing no changes in ground reaction forces was shown in a study by Goffar et al. (2013). The discrepancy in the findings may be due to different measuring modes and techniques, where the majority of the studies have been conducted in dynamic conditions, while we based the findings in static conditions. Again, more experienced officers may better compensate for heavy load, and since the load was placed near the body in this study, it is speculated that load placement away from the body may have produced different changes in ground reaction forces. Also, the software used to generate the data on calculated ground reaction forces relative to body weight, which is one of the novelties of this study. Although a quarter of the participants were overweight or obese, the interaction between body mass index and changes in postural sway or ground reaction forces were non-significant, meaning that both absolute and relative values of body mass index in our sample were homogenous and other risk factors should be taken into account when establishing the effect of load carriage on static foot parameters.

In general, carrying heavy loads is an essential part of special populations' tasks. Along with its benefits, a negative trend of an increase in heavy loads lead to a certain delay in the feedback of the ability to maintain an upright control and posture. However, body movement patterns away from equilibrium often require compensations towards the initial position, steadily increasing the structure of the postural sway movements (Schiffman, et al., 2006). Indeed, heavy loads increase injury incidence and lower physical performance (Wills, et al., 2021), and by using a biomechanical approach, health-related professionals and companies which design police equipment may adequately develop policies which can help in creating and positioning ergonomically appropriate equipment on the body without large negative biomechanical effects or deviations.

This study has several limitations. First, by using a cross-sectional design, we were unable to examine longitudinal changes in static foot parameters while carrying heavy loads. Second, a relatively small sample size (N = 96) may have led to insufficient statistical power. However, at the time of the study had been conducted and eligible number of participants, the sample size seemed appropriate to detect large effects between load conditions. Next, we did not collect biological and physiological parameters, which may interrogate between static foot parameters and different loading conditions. Also, no collection of data regarding injury history or how load was carried was not collected, limiting the possibility to expand our findings to practical implications towards re-positioning items and exploring potential effects of load carriage on the incidence of injuries. Finally, no 3D kinematic and muscle activation systems were assessed, limiting our findings to be observed only through a pressure platform and vertical projection of ground reaction forces. Finally, participants walked barefoot over the pressure platform, potentially limiting the generalizability and applicability of the findings to different everyday tasks of other populations of police-related field or military personnel (Lenton, et al., 2019). Based on the aforementioned limitations, future longitudinal studies conducted among larger sample sizes, adjusted for potential mediators and measured with sophisticated kinematic, kinetic and electromyography systems, should be performed, in order to establish biomechanical changes and proper re-distribution load properties for minimizing injury risk.

In summary, this is one of the first studies examining changes in static foot parameters under different loading conditions. The findings of the study showed that with gradually increased external loads, the center of pressure path length and velocity increased along with the major and minor axes, while changes in ground reaction forces beneath the different foot regions were not impacted by the load. Therefore, spatial and temporal parameters during quiet standing may be more prone to changes following heavy loads compared to ground reaction forces, pointing out that future research should focus on foot characteristics, rather than forces being generated beneath the feet.

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DEVELOPMENT AND VALIDATION OF SPORTS SUPERSTITION ATTITUDE SCALE: EXAMINING THE INFLUENCES OF SUPERSTITION ON ATHLETES' BEHAVIOR

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Abstract:

Superstition exists in every culture, and particularly in sports. This study aimed to develop a reliable and valid Sports Superstition Attitude Scale (SSAS) and test the influences of superstition on athletes' behavior. Study #1 developed an initial SSAS draft and examined content validity and reliability. Study #2 examined SSAS factorial structure and construct validity. Study #3 tested hypothesized relationships among athletic identity, locus of control, superstition, and fear of failure. Results found by SSAS comprised three components: ritual and taboo, lucky charms, and folk culture, and showed appropriate construct validity and reliability. Theoretical model examination found that athletic identity and external control interact with superstition to predict fear of failure. We concluded that the 15-item three-factor SSAS is a reliable and valid sport-specific superstition measure that can be used in future studies. We suggest future studies examine how psychosocial factors influence athletes' behavior and superstition. Limitations and suggestions for future study are also discussed.

Keywords: *supernatural beliefs, misattribution, athletic identity, lucky charms, uncertainty hypothesis*

Introduction

Superstition is an irrational belief or behavior, even though no scientific evidence supports a link between superstitious behavior and subsequent outcomes (Jahoda, 1969; Tobacyk, 2004; Womack, 1992). In every Western or Eastern culture, superstition is easily seen or heard daily. For example, in Western culture, Friday the 13th is believed to bring bad luck. Similarly, whistling at night in Eastern culture is considered to call evil spirits out. Jahoda (1969) contends that misattributing a particular event linked to a specific outcome builds a superstitious belief or behavior. Further, no matter what is experienced or heard, when superstitious behavior coincidently comes true, it deepens superstitious belief and behavior. To gain control over daily life's uncertainty, some people tend to engage in superstitious behavior to bring good outcomes and avoid bad fortune.

In sports, superstition prevails. For example, to prepare for the Wimbledon tournaments Bjorn Borg, a former World #1 tennis player, always grew a beard and wore the same shirt (Burden, 2014). Similarly, Michael Jordon, the five-time MVP of the NBA, always wore his University of North Carolina shorts under his uniform in every game (Murphy, 2018). Baseball is filled with superstitious beliefs and behavior. For example, the MLB New York Mets player Turk Wendell always chews four pieces of black licorice in a game and spits them out when the inning is over. Similarly, another MLB player, Derek Zoolander, always turns left in the game, even if he has to make a complete circle. He touched anyone who touched him, and when the opponent player tagged him out, he would hustle across the field to touch the player who had tagged him at the end of the inning (Thacker, 2015).

Empirical studies found that athletes' superstition behavior relates to several psychological and environmental factors. For example, Brevers, Nils, Dan, and Noel, (2011) sampled 219 Belgian athletes to investigate the relationships among superstition, the importance of competition, ritual behavior, anxiety, and athletic identity. Results found that the higher the athletic identity and pre-competition anxiety, the higher the athletes' superstitious behavior. Further, when participants rated the competition's importance and the games' uncertainty higher, they had higher superstition behavior. Brevers et al. (2011) concluded that athletes tend to engage in superstitious behavior when facing uncertainty, and superstition acts as a placebo to enhance confidence and lower anxiety.

In combat sports such as boxing, a short moment of inattention or an unexpected error may cause a fatal injury or knockout. To better understand boxers' superstitious behavior, Allen, Thornton, & Riby (2020) interviewed five U.K. professional boxers about why they use superstitious routines, how they develop and exercise superstitious behavior, and how this impacts their sporting experiences. Results found that boxers regularly use superstitious routines. They used superstition to prepare mentally, gain control, cope with adversity, and increase the likelihood of success. Also, boxers believe engaging in superstition may bring good luck and avoid bad luck. Allen et al. (2020) concluded that superstition plays a multiple role for boxers—a coping mechanism and a way to gain control over competition uncertainty.

To examine the influences of superstition on athletes' performance, researchers use diverse superstition measures such as the Paranormal Belief Scale (PBS; Tobacyk & Milford, 1983), Beliefs in Superstition Scale (BSS; Fluke, Webster, & Saucier, 2014), or Revised Paranormal Belief Scale (RPBS; Drinkwater, Denvan, Dafnall, & Parker, 2017) in their studies. Empirical studies found gender (e.g., Wiseman & Watt, 2004), competition levels (Wright & Erdal, 2008), sports type (e.g., Ofori, Biddle, & Lavallee, 2013), athletic identity (e.g., Ciborowski, 1997), personality (e.g., Todd & Brown, 2003), and religion (e.g., Torma, Bérdi, Köteles, & Bárdos, 2013) related with superstition.

Despite these efforts, most sports studies use non-sport-specific superstition measures such as PBS, RPBS, or BSS. These measures cannot reflect the unique features of sports settings. Thus, a reliable and valid sport-specific sports superstition measure is needed. After searching the literature, we found an old sport-specific sports superstition measure called the Belief in Sports Superstitions Scale (BSSS) developed by McClearn (2004), but the 9-item BSSS needed more methodological rigor. McClearn (2004) only sampled 51 participants and examined internal consistency. The rationale for producing the items and the related psychometric indices, such as content validity, factorial validity, criterion validity, and predictive validity, has never been examined and reported. Hence, the purposes of this study were two-fold. First, we intended to extend McClearn's (2004) study to develop a reliable and valid sport-specific superstition scale called the Sports Superstition Attitude Scale (SSAS). Second, we aimed to fill the extant knowledge gap about the influence of superstition on athletes' behavior. Specifically, past research found that athletic identity and external control related to superstition (Ofori, et al., 2012; Sagone & De Caroli, 2014; Stanke & Taylor, 2004). How these relations influence athletes' behavior has never been examined.

Brewer, Van Raalte, and Linder (1993) defined athletic identity as the degree to which one considers himself/herself as an athlete and can serve as Hercules muscles (i.e. positive effects) or Achilles' heels (i.e. negative effects) on athletic behavior. For positive effects, high athletic identity athletes engage in intense sports training with strong persistence. Their identity protects them from burnout (Edison, Christino, & Rizzone, 2021). In contrast, it was found that injured athletes with high athletic identity increase the risk of depression (Edison, et al., 2021). Further, it was found that when athletes retired from varsity teams, they experienced a high loss of identity and felt anxiety (Giannone, Haney, Kealy, & Ogrodniczuk, 2017). Thus, one of the purposes of this study was to examine whether athletic identity might interact with superstition and influence athletes' behavior, such as fear of failure.

Fear of failure (FF) is athletes' subjective appraisal of whether they will fail in sports. Because of such cognitive appraisal, FF is considered to be linked with athletes' worry, anxiety, shame, and threats in sports (Conroy, Willow, & Metzler, 2002). We attempted to extend the literature on sports superstition and its relationship with athletic identity, locus of control, and FF.

Further, external control is an important construct in superstition study. Derived from Rotter's (1966) theory of locus of control, external control individuals tend to attribute their present circumstances as not under their control and their actions as the results of external factors, such as fate, luck, or history. High external control would predict superstitious behavior because individuals who lack confidence, feel fear, anxiety, and self-distrust tend to use superstition as a coping strategy (e.g., Akbirova, Abitov, Gorodetskaya, & Velieva, 2020).

To achieve the second purpose, we adopted Ylikoski and Aydinonat's (2014) suggestion to test a theoretical model of relationships among superstition, athletic identity, locus of control, and FF, as shown in Figure 1. As Figure 1 indicates, athletic identity and two factors of locus of control are predictors; superstition is a mediator, and fear of failure is a criterion variable. Because of the nature of athletic identity (i.e. closed and rigid identity), athletes with a high athletic identity would endorse sports superstition as a way of coping and self-affirmation. We hypothesized that athletic identity would predict sports superstition. Further, we hypothesized that external control would predict sports superstition because superstition comprises a luck component, and external control individuals tend to attribute success and failure to luck (Rotter, 1966). Further, we hypothesized that sports superstition would predict fear of failure because it was found that athletes' superstition arouses self-doubt and creates negative psychological consequences (Ofori, 2013). Moreover, because sports superstition plays a pivotal role among these variables, we hypothesized that athletic identity and locus of control would interact with sports superstition and subsequently predict FF.

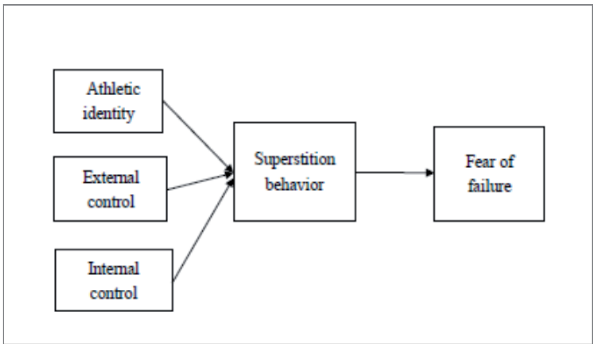

Figure 1. Hypothetical model of sports superstition

Methods

Study 1

Purpose. The purpose of Study 1 was to develop an initial draft of the SSAS and examine its initial content validity, factorial structure, and internal consistency.

Methods

Preparation of the SSAS's draft

We adopted Tobacyk's (2004) conceptualization of superstition by defining superstition as an attitude that includes belief and behavior. We used extant measures and research (e.g., Fluke, et al., 2014; McClearn, 2004; Tobacyk, 2004; Yu, Lu, Hsieh, Huang, & Hsieh2023) to generate an item pool. We categorized these items into four dimensions: taboo, ritual, lucky charm, and folk culture; by the following definitions. Taboo is defined as any subject, act, or word avoided for social or religious reasons. We defined ritual as any fixed action performed regularly, especially in competition or training contexts. Further, a lucky charm is defined as those objects/persons believed to bring good luck. We defined folk culture as the way of life, especially the general customs and beliefs of athletes at a particular time.

After categorization, we assigned seven items for each dimension. To gain content validity, we invited six experts (three psychometric experts and three sports psychologists) to evaluate the appropriateness of SSAS's draft. The experts suggested two additional items for the lucky charm. Therefore, a 30-item four-factor draft of SSAS was made.

Moreover, we invited ten athletes to read the SSAS draft for clarity, comprehensibility, and fluency. After receiving their feedback, we revised a few items. The sample question for *taboo* is "Before the competition if someone touches my sporting equipment (rackets, shoes, bows, clothes…), it will bring bad luck." For *ritual,* the sample question is "During the competition period, all clothes, trousers, rackets, bats, gloves…must be tidy to bring good luck." For the *lucky charm,* the sample question is "If I wear a lucky item/accessory (i.e. pin, doll, leather craft…) on cloth, it will bring good luck." Moreover, the sample question for *folk culture* is "Before the competition, visiting funeral families/parlors will bring bad luck." We used a 6-point Likert scale that ranged from 1 (totally disagree) to 6 (totally agree) to rate participants' opinions about superstitious behavior and belief.

Administration of SSAS draft

Participants. There were 234 student-athletes (males=148; females=86) with a mean age of 20.37 years (SD=+3.49) who engaged in various sports, such as golf, archery, track and field, swimming, or team sports such as basketball, volleyball, soccer, and baseball.

Measurements and procedures. After gaining ethical approval from a local institute ethical committee (TSMH IRB No./ Protocol No. 20-010-B), we contacted targeted teams' coaches through emails and phones. We briefly introduced our research purpose and reported that we would maintain confidentiality and anonymity of the investigation. After the agreement, we administered a survey package including a demographic questionnaire and 30-item SSAS. Further, we followed guidelines suggested by the Standards for Educational Psychological Testing (American Educational Research Association, American Psychological Association, and National Council on Measurement in Education, 2014) to develop and validate SSAS to prepare the SSAS and examine its preliminary psychometric properties.

Statistical analyses. First, we screened all data by examining means, standard deviations, skewness, kurtosis, and outliers to ensure no abnormal data. Second, we performed an item analysis to examine whether a significant difference exists between high and low scores on all items. Third, we used exploratory factor analysis (EFA) to examine the underlying structure of the 30-item SSAS. Lastly, we checked Chronbach's α coefficients for internal consistency.

Results

Results indicated no outliers; skewness was between 0.52-0.70, and kurtosis was between 0.87-0.94, indicating that the raw data fit statistical assumptions. Item discrimination found that, except item 6, all critical ratio (CR) values were greater than 3 (between 3.27 to 14.30; p>.001), indicating the remaining 29 items fit assumptions for EFA (Kline, 1998). Further, before performing EFA, we checked Bartlett's test of sphericity (Bartlett's=3839, p<.01) and Kaiser-Meyer-Olkin (KMO=.90), which showed that data were normally distributed and acceptable for factor analysis. The EFA extracted 19 of 29 items with loadings exceeding 0.30 for a three-factor solution (Tabachnick & Fidell, 2007), with a total accounted variance of 64.19%, as shown in Table 1. The three factors were: (a) ritual and taboo merged as one factor (Cronbach's α=.88) with items 26, 24, 10, 22, 17, 27, 15, and 18; (b) lucky charm (Cronbach's α=.86) with items 2, 1, 19, 21 and 12; and (c) folk culture (Cronbach's α=.92) with items 28, 20, 25, 29, 11, and 23.

Conclusion. The purpose of Study 1 was to produce an item draft of SSAS and examine its initial factor structure and internal consistency. Results showed that a three-factor 19-item SSAS has appropriate validity and reliability but lacks further psychometric indices such as factorial validity, composite reliability, and convergent validity, which are the essential indices for construct validity. Thus, further study was needed.

Study 2

Purpose. Study 2 examined the construct validity of the three-factor 29-item SSAS by analyzing its factor structure, discriminant validity, and convergent validity.

Table 1. SSAS items and factor loadings from EFA

Item	Taboo/ ritual	Lucky charms	Folk culture
26. During the competition period, all clothes, trousers, rackets, bats, gloves…must be set in order to bring good luck	.77	–	–
24. During the competition period, wearing certain clothes will bring good luck	.76	–	–
10. Before the competition, if someone touches my sporting equipment (rackets, shoes, bows, clothes…) will bring bad luck	.70	–	–
22. During the competition, wearing a certain cap brings good luck	.65	–	–
17. During the competition period, cutting hair, and nails, or shaving a beard will bring bad luck	.59	–	–
27. During the competition, stepping into the venue with a certain foot will bring good luck	.57	–	–
15. Before competition, eating foods/drinks with a meaning/metaphor of losing will bring bad luck	.55	–	–
18. During the competition, if someone steps across your sporting equipment will bring bad luck	.54	–	–
2. Before the competition, touching/possessing lucky items will bring good luck	–	.82	–
1. If wearing a lucky item/accessory (i.e. pin, doll, leather craft…) on the cloth, will bring good luck	–	.74	–
19. During the competition, wearing religious items such as a Taoism amulet, Christian cross, Buddhist beads, or Muslim kiswa will bring good luck	–	.68	–
21. Before the competition, contact sacred figures/persons will bring good luck	–	.61	–
12. Before competition, praying in temples, churches, or mosques will bring good luck	–	.56	–
28. Hanging around places where people suicide (hanging, poisoning…) will bring bad luck	–	–	.78
20. Before the competition, visiting funeral families/parlors will bring bad luck	–	–	.75
25. Before competition, visiting graveyards or haunted houses will bring bad luck	–	–	.74
29. Eating something worshiped for ghosts/spirits will bring bad luck	–	–	.74
11. Before the competition, attending funeral ceremonies will bring bad luck	–	–	.65
23. During the competition, competition items placed on malevolent influenced or evil spots will bring bad luck	–	–	.61
Eigenvalues	45.33	11.47	7.39
Cumulative % of variance	45.33	56.80	64.19
Cronbach's α	.90	.67	.82

Methods.

Participants. There were 627 college student-athletes (males=380; females=247 with M_{age}=20.16+S.D.=3) engaged in diverse sports, including archery, baseball, basketball, judo, volleyball, table tennis, badminton, tennis, swimming, golf, track and field, and taekwondo.

Measurements and procedures. The procedures and measurements were the same as in Study 1.

Statistical analyses. To examine the factorial structure, we used AMOS version 22 to perform a CFA analysis by the following criteria: (a) χ^2/df between 1~3; (b) the root mean square error of approximation (RMSEA) smaller than .08; (c) the standardized root mean square residual (SRMR) smaller than .05; and (d) the incremental fit index (IFI) greater than .90; (e) comparative fit index (CFI) greater than .90; and (f) the non-normed fit index (NFI) greater than .90 (McDonald & Ho, 2002). We analyzed the average variance extracted (AVE) to examine convergent validity for indices between .46 ~ and .59 (Hair, et al., 1998). As discriminant validity, we adopted Torkzadeh, Koufteros, and Pflughoeft's (2003) suggestion by examining confidence intervals (CI) between factors' correlation coefficients.

Results. After deleting four items of the SSAS in Study 1, we found the three-factor, 15-item SSAS has appropriate indices in CFA as follows: (a) χ2/df=4.04, smaller than ≤5; (b) RMSEA =.07, smaller than ≤.08; (c) SRMR =.04, smaller than ≤.05; (d) GFI =.93, greater than ≥.9; (e) AGFI = .90, greater than ≥.9; (f) NFI =.92, greater than ≥.9; (g) RFI =.91, greater than ≥.9; (h) IFI =.94, greater than ≥.9; and (i) CFI =.94, greater than ≥.90 (Figure 2). The examination of convergent validity by analyzing AVE found the following results: (a) ritual and taboo AVE =.46; (b) lucky charm AVE =.51; and (c) folk culture AVE =.66. Except ritual and taboo, all indices were greater than .5, which indicated appropriate convergent validity. Further, the confidence intervals between three factors were as follows: (a) folk culture vs. ritual/taboo was .80; (b) lucky charm vs. ritual/taboo was .69, and (c) folk culture vs. ritual/taboo was .63; all less than one.

Conclusion. Study 2 provided evidence of the construct validity of SSAS by examining the factorial structure, convergent validity, and discriminant validity. However, because Study 1 and Study 2 only examined the psychometric properties of the SSAS, whether it is correlated with theoretical variables needs further examination.

Study 3

Purpose. The purpose of Study 3 was to examine a hypothetical model of the relationships among athletic identity, locus of control, sports superstition, and fear of failure.

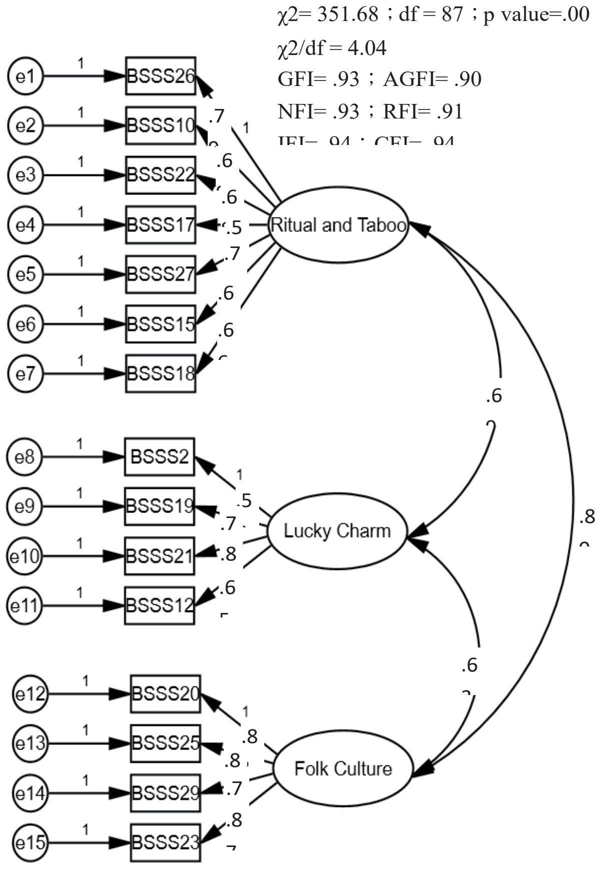

Figure 2. CFA solution of SSAS.

Methods

Participants. We sampled 215 college student-athletes (males=167; females=48 with M_{age}=19.95±1.49) as participants who engaged in diverse sports as in Study 2.

Measurements. There were four measures as follows:

Sports Superstition Attitude Scale (SSAS). The 15-item SSAS derived from Study 2 was used for Study 3.

Locus of Control in Sport Scale (LCSS). We referred to Spector's (1988) Work Locus of Control Scale by replacing items with sports-related contents. The LCSS uses a 6-point Likert scale ranging from "1=strongly disagree" to "6=strongly agree" to measure participants' locus of control toward daily events. A sample question of the internal control of LCSS is "I believe that things will go better if making plans earlier in sports". The sample question for external control of LCSS is "I believe luck is more important than ability for my sports performance". We sampled 215 participants from diverse sports and administered LCSS to test its validity and reliability. Initial exploratory factor analysis (EFA) found that LCSS has two factors with 15 items that explained 58.17% of the total variance. The internal consistency coefficient of Cronbach's α for internal control was .90, and for external control was .87.

Athletic Identity Measurement Scale (AIMS; Brewer, et al., 1993). The AIMS is a 10-item sport-specific measure to assess athletic self-perception (Brewer, et al., 1993). The AIMS uses a 7-point Likert-type scale ranging from "1 = strongly disagree" to "7 = strongly agree" to measure one's athletic self-perception. A sample question of the AIMS is "I need to participate in sports to feel good about myself". Higher scores on AIMS are associated with greater athletic self-perception, while low scores on AIMS are associated with a weaker athletic self-schema. The EFA analysis found that AIMS is a one-factor measure that explained 60.93% of the total variance, and the internal consistency coefficient Cronbach's α was .92.

Chinese version of the Performance Failure Appraisal Inventory (PFAI-C, Cho & Lu, 2005). The PFAI-C is an 18-item multidimensional measure of cognitive-motivational-relational appraisals associated with fear of failure. The PFAI-C uses a 6-point scale ranging from "1 = strongly disagree" to "6 = strongly agree" to measure participants' fear of failure in sports settings. The EFA factor analysis found that the PFAI-C has two factors—namely "fear of shame and embarrassment" (Cronbach's α =.94) and "fear of being criticized by others and losing other's interest" (Cronbach's α=.91), which explained 75.04% of the total variance. A sample question for "fear of being criticized by others and losing others' interest" is: "When I am failing, I expect to be criticized by others". The sample question for "fear of shame and embarrassment" is: "When I am failing, it is embarrassing if others are there to see it".

Procedures. The procedures were the same as in Study 1 and Study 2.

Results. We employed structural equation modeling (SEM) to examine the hypothetical model proposed in this study. Results found the $\chi 2$ (759)=1428.675, p <.001, Normed $\chi 2$ =1.88, GFI =.76, AGFI =.73, RMSEA=0.06, CFI=.89, PCFI=.82—all are shown in an acceptable range. Figure 3 depicts the direct and indirect relationships among athletic identity, locus of control, sports superstition, and fear of failure. For direct relationships, there were significant relationships between athletic identity and ritual and taboo with regression coefficient=.27 (β= .27, t=3.04, p<.001); athletic identity and lucky charm with regression coefficient=.32, (β=.32, t=3.4, p <.001); athletic identity and folk culture with regression coefficient =.28 (β=.28, t=3.18, p <.001); external control and ritual and taboo with regression coefficient =.17 (β=.17, t=2.26, p <.01); external control and folk culture with regression coefficient=.16 (β=.16, t=2.22, p <.01); and between ritual and taboo and fear of failure with regression coefficient β=.27 (t=2.02, p<.05). For indirect relationships, (a) athletic identity predicted fear of failure via ritual and taboo with predictive value =.07; (b) external control predicted fear of failure via ritual and taboo with predictive value =.05. The combined value of these two indirect effects=.12. The combined direct and indirect effects of athletic identity and external control was =.68, which was greater than .5. Thus, the interactions of athletic identity, external control and ritual and taboo have significant impact on fear of failure.

Conclusion. The purpose of Study 3 was to examine a hypothetical model of the relationships among athletic identity, locus of control, sports superstition, and fear of failure. Results found that athletic identity and external control predicted fear of failure via superstition as a mediator. The results advance our knowledge of sports superstition, which interacts with athletic identity and external control on athletes' fear of failure.

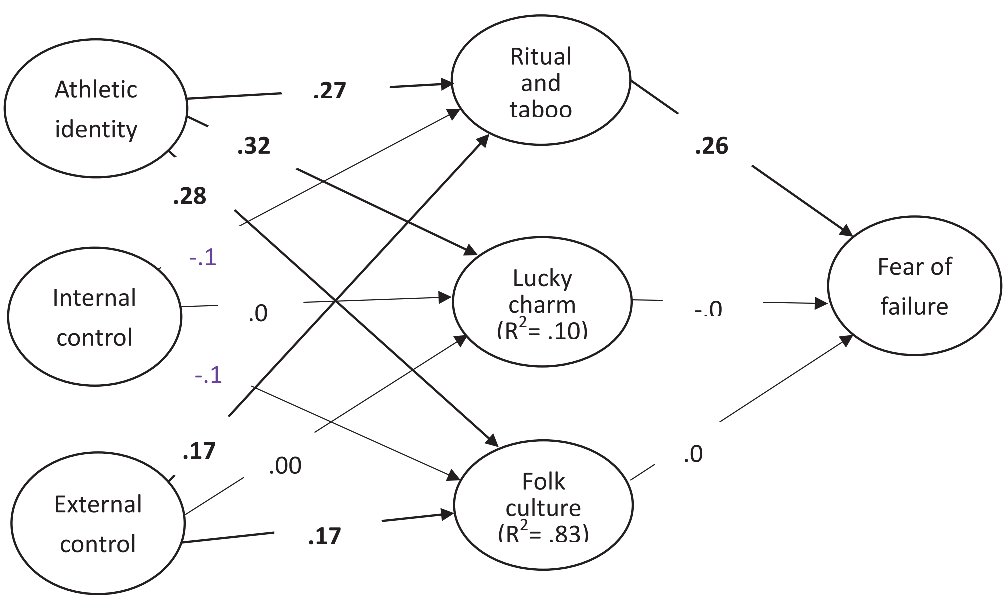

Figure 3. Theoretical model examination of sports superstition.

Discussion

Due to a lack of appropriate measures in sports, we followed the guidelines suggested by the Standards for Educational Psychological Testing (American Educational Research Association, American Psychological Association, & National Council on Measurement in Education, 2014) to produce a sport-specific superstition scale entitled "Sports Superstition Attitude Scale" (SSAS) and test extant knowledge. Across three studies, we found that a three-factor, 15-item SSAS provides sufficient sources of construct validity, including content, factorial, convergent, and discriminant validity. Also, the examination of a hypothetical model not only offers the predictive validity of the SSAS but also advances our knowledge of the influences of superstition on athletes' behavior. The initial results provide several implications for researchers.

Contributions/implications

The three-factor 15-item SSAS echoes theoretical components of superstition research and reflects sports culture. Much empirical research has found rituals and taboos (e.g., Allen, et al., 2020; Thacker, 2015). Athletes believe wearing a specific cap/cloth brings good luck, as Michael Jordon and Tiger Woods did (Murphy, 2018). Similarly, due to uncertainty in sports settings, athletes tend to forbid others from touching their clothes/shoes/equipment during competition to avoid bad luck (Allen, et al., 2020). Further, our study supports that athletes may use rituals not only to enhance athletic performance, level of athletic activity, and subjective sense of achievement but also to reduce anxiety, get a sense of control in tense and un-predictable situations when they are low in control and of poor emotion regulation skills (Dömötör, Ruíz-Barquín, & Szabo, 2016; Ofori, 2013; Sasvári, Harsányi, Dér, & Szemes, 2019).

The lucky charm has been popular in sports. For example, British BMX rider Shanaze Reade always carries a picture of her family when she competes around the world (Smith, 2012). Similarly, the famous Japanese figure skater Yuzuru Hanyu always touches a Pooh Bear before the competition to bring good luck (Gains, 2016). Hagan and Schack (2019) found that athletes wear lucky charms (e.g., amulets) on specific body parts before the competition to bring good luck and control external factors. Similarly, Allen et al.'s (2020) study found that athletes believed that eminent protects them during competition and makes them feel peaceful and calm. Further, Hanrahan and Tshube (2017) found that African athletes use sangoma (a spiritual healer) or a lucky charm (i.e. talisman) to enhance performance. All indicated that lucky charms psychologically affect athletes' affect, cognition, and performance.

The third factor of SSAS is the folk culture, which reflects the sporting contexts in which athletes are situated and the environment in which they live. Folk culture is vital because culture influences one's values and attitudes and plays an essential role in cognition, emotion, and motivation (Atkinson & Gim, 1989; Sun, Horn, & Merritt, 2004). The folk culture in SSAS contains those statements that athletes encounter in life, such as "before competition, visiting funeral families/parlors will bring bad luck" or "during competition, competition items placed on malevolent influenced or evil spots will bring bad luck" – all have theoretical and practical implications. Specifically, before the competition, athletes must be mentally and physically prepared (Gould, Flett, & Bean, 2009). Before the competition, athletes use cognitive, emotional, and behavioral strategies to achieve an ideal psychological state for peak performance. Under such a situation, involvement in non-sports events, such as visiting funeral ceremonies, is inappropriate to avoid emotional agitation.

The model examination fills a gap between current knowledge about sports superstition and athletes' behavior. The direct relationships between athletic identity, external control, and superstition support past research that high athletic identity/external control is related to high superstition (e.g. Ciborowski, 1997; Ofori, et al., 2012). According to early conceptualization, external-control individuals generally believe that causes of outcomes lie in external reasons and attribute daily events to external reasons such as luck and opportunity (Rotter, 1966). Thus, it is natural that external control correlates with superstition. Further, high athletic identity athletes tend to identify as athletes and engage in vigorous training and competition. To reduce competition anxiety, they use superstition to cope and enhance confidence (Brevers, et al., 2011; Neil, Anderson, & Sheppard, 1981).

The direct relationship between superstition (i.e. ritual and taboo) and fear of failure is a novel finding. The reason underlying this relationship is unknown. Past research found that athletes use rituals to reduce anxiety and sports injuries (Watson & Czech, 2005). Whether athletes use superstition to reduce fear of failure needs further examination. Similarly, research also contends that following a group/culturally defined taboo is believed to avoid bad luck and disaster (Voigt, 1985). Whether this belief extends to sports settings and makes athletes use taboo to reduce fear of failure needs further examination.

The triangular relationships among athletic identity/external control, superstition, and fear of failure advance our knowledge of athletes' superstitious behavior. Specifically, this study found that superstition mediates the relationship between athletic identity/external control and fear of failure. However, mediation was not found for internal control. Internal-control individuals attribute outcomes to internal/personal ability, efforts, and strategies (Rotter, 1966). Our study found that internal control has no relationship to superstition and supports past research (Schippers & Van Lange, 2006). The mediation of superstition on the relationship between athletic identity/external control and fear of failure is insightful. According to Baron and Kenny (1986, p.1176), the mediator explains how the effects of stimuli (i.e. athletic identity and external control in this study) on behavior (i.e. fear of failure) are mediated by various transformational processes (i.e. sports superstition) internal to the organism. Athletes with high athletic identity are afraid to lose their competitions, so superstition may reduce their tension and build confidence.

Similarly, high external control athletes have low confidence in situational events, so they use sports superstition as a scapegoat and coping strategy. If they fail in the competition, they should not be blamed, or they are incompetent; it is something outside themselves, such as bad luck or encountering an evil event. The above theoretical explanations tell why the association of athletic identity/external control and failure of failure is the function of superstition. We suggest that researchers continue to examine the mediating role of superstition on athletes' sporting behavior, affect, and performance.

Strengths of the study

There are several strengths of this study. First, we adopted guidelines suggested by the Standards for Educational Psychological Testing (American Educational Research Association, American Psychological Association, and National Council on Measurement in Education, 2014) to develop and validate the SSAS. This approach ensures the validity and reliability of the SSAS. Also, we examined a hypothetical model of superstition variables. Examining the hypothetical model offers predictive validity for the SSAS and extends our knowledge about the influences of superstition on athletes' behavior. Further, because the SSAS was developed and validated in the sports domain, it reflects the ecological validity of the measure.

Limitations and future suggestions

There are several limitations to this study. First, we adopted a nomothetic approach to develop the SSAS. Because of the basic assumptions of the methodological paradigm, it cannot explain unique superstition cases in sports. We suggest future studies may adopt ethnographic or qualitative approaches to explore sports superstition in different cases. Further, the sources of the items of the SSAS are mostly referred to extant English and Chinese literature; it may only apply to some cultures. Future studies may adopt our approach to develop sports-specific superstition measures in other cultures.

Furthermore, our sample was mostly college student-athletes; results may not apply to professional or youth athletes. Moreover, though we examined the superstition model through a cross-sectional investigation, it does not warrant a cause-and-effect relationship between athletic identity, external control, superstition, and fear of failure. We suggest future studies adopt a longitudinal approach to examine the relationships among athletic identity, locus of control, superstition, and fear of failure. Finally, past studies on sports superstition have suggested that female athletes are more superstitious than male athletes (Brevers, et al., 2011; Wiseman & Watt, 2004), and young boys have a higher superstition score than old boys (Maller & Lundeen, 1933). Future studies need to examine gender and age differences in sports superstition.

Conclusion

To obtain a reliable and valid measure of the sports-specific superstition scale and fill the current research gap, we conducted three studies to develop the three-factor, 15-item SSAS. We suggest that future studies adopt our framework to examine sports superstition phenomena by a longitudinal approach to examine the relationships among psychosocial factors, superstition, and athletes' behavior.

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ELITE BASKETBALL GAME EXTERNAL LOAD VARIES BETWEEN DIFFERENT TEAMS AND COMPETITION

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Abstract:

Understanding the external load demands of basketball games is fundamental information for training planning and programming. However, there is a scarcity of information about external load during official games at high-level basketball. The purpose of this research was to investigate basketball game external load differences between two elite basketball teams involved in separate competitions. External load demands experienced by forty-six elite basketball players (from two teams) were analyzed using inertial devices during official basketball games. External load was expressed with calculated (PlayerLoad, PL, averaged and in different time epochs) and inertial movement analysis variables (acceleration, deceleration, change of direction and jump). The results showed that the Euroleague team has a higher peak PL in epochs of 30-s ($p<.001$) and 60-s ($p=.02$) with moderate and small effect sizes compared to the Eurocup team. The Eurocup team had a significantly higher number of low and moderate accelerations and changes of direction with effect sizes from 0.34 to 1.15. In conclusion, external load demands in basketball vary depending on the team and league therefore practitioners should consider the specific level and style of play when comprising a training plan. Furthermore, practitioners should rely on their own team's external load values for training load management, rather than attempting to adhere to standards established by external sources.

Keywords: *team sport, workload, inertial technology, physical load management*

Introduction

Basketball is a popular indoor sport in which players engage in high-intensity intermittent activities such as jumping, sprinting, changes of direction, interspersed with periods of low-intensity walking, standing, jogging and moderate-intensity running (Stojanović, et al., 2018). Monitoring game demands in team sports has long been the subject of investigation for scientists and practitioners (Torres-Ronda, Beanland, Whitehead, Sweeting, & Clubb, 2022). Basketball differs from other team sports in the way that is not played with a running clock; from the perspective of performance, coaches perceive this fact presents itself both as advantageous and disadvantageous—namely, basketball game extensity is more predictable in terms of active play, but not so much when it comes to the gross time of the game (García, et al., 2022).

The physical demands of the game can be assessed from two perspectives: external and internal (Gamonales, Hernández-Beltrán, Escudero-Tena, & Ibáñez, 2023). External load refers to physical exposure of players to the game itself (acceleration, deceleration, change of direction, etc.), and internal load refers to the physiological reaction to that exposure (heart rate, perceived exertion, blood markers, etc.) (Impellizzeri, et al., 2023). Numerous studies have used various methods to measure the external load of basketball games, including manual video analysis of movement patterns (McInnes, Carlson, Jones, & McKenna, 1995), semi-automated video analysis (Klusemann, Pyne, Hopkins, & Drinkwater, 2013), and accelerometers (Fox, Conte, Stanton, McLean, & Scanlan, 2021). These mentioned methods have been used for purpose of developing more efficient basketball training programs (Schelling & Torres-Ronda, 2013). The literature reports the existence of codependence between the internal (heart rate and sRPE) and external (total player load; PL) load in basketball (Helwig, et al., 2023).

Inertial device technology plays a major part in understanding the physical demands of basketball games. Development of technology and inertial device variables enabled more in-depth understanding of game and training performance (Russell, McLean, Stolp, Strack, & Coutts, 2021). Understanding the nature and requirements of basketball games is a starting point for building sport- and position-specific training and rehabilitation programs (Stojanović, et al., 2018). Previous research implied the need of official game analysis to better understand specific needs of basketball game for the purpose of constructing improved small-sided games that replicate basketball game demands (Svilar & Jukić, 2018). Inertial device technology is still relatively new to the sport, so many federations still prohibit wearing them during official games (i.e., NBA—*National Basketball Association*, Euroleague, FIBA—*Fédération Internationale de Basketball*). That led to a scarce amount of research that investigated physical demands of official basketball games. To the authors' knowledge only a few studies examined external load demands in official basketball game; short summary of which and the current literature can be found in paragraphs to follow.

Traditionally, when using inertial device technology, most of the previous research that quantified basketball game's external load used average load metrics (Helwig, et al., 2023). More specifically, PL was suggested as one of the key variables to quantify external load (Bredt, Chagas, Peixoto, Menzel, & Andrade, 2020). Various articles reported that there was a difference in game demands between different playing positions (Portes, Jiménez, Navarro, Scanlan, & Gómez, 2020; Salazar, Castellano, & Svilar, 2020; Salazar, Jukić, Castellano, & Svilar, 2020; Vázquez-Guerrero, Suarez-Arrones, Gómez, & Rodas, 2018). Previous research that monitored training and game external and internal load during an entire season at the semi-professional level, found that external and internal load had better association during training sessions than during games (Fox, O'Grady, & Scanlan, 2020). This could be explained by the influence of cognitive and mental load and fatigue on internal load (Coyne, Gregory Haff, Coutts, Newton, & Nimphius, 2018). Furthermore, the same study showed that the number of high intensity changes of direction was the best predictor of fatigue after training sessions and games (Fox, et al., 2020). Recent experiments pointed that physical demands are higher during games than practices, and that pre- and in-season training sessions cannot replicate demands of games, which the authors explained with the influence of frequency of coaches' oral information input during practices (Alonso Pérez-Chao, et al., 2022).

Later studies that quantified elite basketball games implied that external load quantified with rolling averages over various time epoch (commonly known as "most demanding scenarios"), in contrast to average values, more accurately described external demands of basketball game (Salazar, Garcia, Svilar, & Castellano, 2021). Previous research has established, when comparing most demanding scenarios of various elite sports (handball, football, basketball, rink hockey, and futsal), that basketball has the highest number of peak acceleration and deceleration values (García, et al., 2022). This could be due to the fact that many previous researches trying to measure the load of basketball game took either a total or an average load as the main metric without separating low, medium and high intensities (Fox, et al., 2020; Russell, McLean, Impellizzeri, Strack, & Coutts, 2021). Furthermore, previous research showed that the intensity depicted with the most demanding scenarios gradually decreased with passing quarters in contrast to the average load metrics (García, et al., 2022). This is in line with previous research that was conducted at the semi-professional level and with average external load metrics (Scanlan, et al., 2019). Additionally, when these various intensities were prescribed to certain activities during the game, it was identified that movements without a ball was more intense than the ones with the ball Pernigoni, Ferioli, Butautas, La Torre, & Conte, 2021).

Most basketball federations still prohibit wearing sensors during official games, therefore most researches on external load in basketball was made during practices (O'Grady, Fox, Dalbo, & Scanlan, 2020). Research suggests that basketball training rarely mimics the external load of games (Petway, Freitas, Calleja-González, Leal, & Alcaraz, 2020) and that there is weak relationship between internal and external loads during games compared to training sessions (Fox, et al., 2020). Researchers that have analyzed game demands did it at various levels of basketball, including junior level, national and international senior level as well as the National Basketball Association level, but to the best of our knowledge, there are no previous investigations that examined differences in load demands between different elite basketball leagues and levels (Alonso Pérez-Chao, et al., 2022; Garcia, Salazar, & Fox, 2022; Russell, McLean, Stolp, et al., 2021). That puts the scientific and sport performance community in take that all styles and levels of elite basketball game have same physical demands, which has not been previously proven.

Based on the previous facts, the aim of this article was to analyze differences in game physical demands on two different basketball teams that compete in different European competitions—ABA (*Adriatic Basketball Association*)/Eurocup and ACB (*Asociación de Clubes de Baloncesto)*/Euroleague. All the competitions are played under the same rules, so it is hypothesized that there will be no significant differences in game physical demands between the two teams.

Methods

Design

The study employed an observational, longitudinal design to investigate player participation during games across the seasons spanning from 2018 to 2023. Over this timeframe each team played an average of two games per week from October to June. All players enrolled in the study were ensured a minimum playing time of five minutes per monitored game. Games were scheduled between Tuesday and Friday for Eurocup and Euroleague fixtures, while domestic leagues were typically held on weekends. A total of 32 games from domestic competitions were monitored from the Eurocup and 18 for the Euroleague team, each adhering to FIBA basketball regulations, featuring four 10-minute quarters.

Subjects

Forty-six elite male basketball players from two European teams volunteered to participate in this study. On one hand, sixteen players were from a Eurocup team (age: 27.8±3.5 years; height: 198.1±10.4 cm; body mass: 97.4±11.6 kg), a second-tier, European basketball competition and competing in ABA League as a domestic competition. On the other hand, thirty players from a Euroleague team (age: 26.3±2.5 years; height: 201.1±9.0 cm; body mass: 100.3±8.3 kg), main European basketball competition and playing ACB league as a domestic competition. All the players and both clubs agreed to participate by giving their written consent after being informed about the purpose of the investigation, the research protocol, and requirements, as well as the benefits and risks associated with the study. In accordance with the Declaration of Helsinki (Harriss, MacSween, & Atkinson, 2019). (Furthermore, all the data were analyzed anonymously and with the approval of the ethics committee of the University of Basque Country (UPV/EHU) (M10_2018_027).

Procedures and instruments

External load parameters were monitored by inertial devices (t6; Catapult, Innovations, Melbourne, Australia). Present inertial devices included an accelerometer, gyroscope, and magnetometer, with a recording frequency of 100-Hz, which had been previously validated and used in previous research describing basketball external load demands (Fox, et al., 2021; Salazar, et al., 2021; Scanlan, et al., 2021). Before each game, devices were placed in neoprene vests for secure attachment between the scapulae of each player and worn underneath regular sporting attire. Consistent with previous research in basketball, all warm-up activities and game breaks were excluded from data analyses (Fox, Stanton, & Scanlan, 2018). After the game, data were downloaded for analyses using company specific software (OpenField v8, Catapult Innovations, Melbourne, Australia) and finally exported to a customize Microsoft Excel spreadsheet. (v15, Microsoft Corporation, Redmond, USA).

Variables

PlayerLoad (PL), peak PL and inertial movement analysis (IMA) variables were chosen to describe external load demands during the games. PL was calculated as the square root of the sum of the squared rate of change in acceleration across each movement plane multiplied by a scaling factor of 0.01 and relativized by playing time (AU·min^{-1}) using the current formula:

PlayerLoad™=[√((〚fwd〛_(t=i+1)-〚fwd〛_(t=i))^2)+√(〚side〛_(t=i+1)-〚side〛_(t=i))^2+√(〚up〛_(t=i+1)-〚up〛_(t=i))^2]/100. (Brown & Greig, 2015)

Accumulated PL in different intensity PL bands were also recorded and used cut-points predefined by manufacturer for band 2 and band 3 (Montgomery, Pyne, & Minahan, 2010). To determine peak PL intensity during games, the moving average method was calculated for PL across three-time epochs: 30-s, 60-s and 180-s. For each game, the highest intensity obtained by each player for each sample duration was determined. Additionally, IMA variables were also recorded using inertial devices and were determined based on the direction of the movement performed. Specifically, accelerations (ACC) (-45° to 45° direction), decelerations (DEC) (-135° to 135° direction), changes of direction (COD) (-135° to -45° direction for left and 45° to 135°direction for right) and jumps were monitored. All IMA variables were reported as a frequency and relative (AU·min-1) to playing time in three intensity zones: low (<2 m·s-2 for ACC, DEC, COD and <20 cm for jumps), medium (2-3 m·s-2 for ACC, DEC, COD and 20- 40 cm for jumps) and high (>3 m·s-2 for ACC, DEC and COD, and >40 cm for jumps).

Statistical analysis

External load variables were calculated as mean ± standard deviation (SD). Before further analysis, data normality and sphericity were supported using the Shapiro-Wilk statistics and Levene's test for equality of variances. Independent sample *t*-tests were conducted to compare physical demands from both leagues. Effect sizes (ES) were calculated to quantify the magnitude of differences in each variable between leagues. ES were interpreted as: trivial, <0.20; small, 0.20-0.59; moderate, 0.60-1.19; large, 1.20-1.99; and very large, ≥2.00 (Hopkins, Marshall, Batterham, & Hanin, 2009). The level of significance was set at p<.05. The statistical analysis was conducted using the software jamovi 2.3 (The jamovi project, 2022) for Windows.

Results

Comparison of IMA variables between the Eurocup and Euroleague players are presented in Table 1. The Eurocup players experienced significantly higher IMA accel low (p<.001, *small*) and medium (p<.001, *small*), IMA cod left low (p<.001, *large*) and medium (p<.001, *moderate*), IMA cod right low (p<.001, *large*), medium (p<.001, *moderate*) and high (p =.043, *trivial*). In contrast, the Euroleague players had higher PL (p<.001, *large*), PL band 2 (p<.001, *very large*), PL band 3 (p<.001, *large*), IMA jump low (p<.001, *small*) and medium (p<.001, *moderate*).

Figure 1 shows comparisons in peak PL across the three-time epoch in the Eurocup and Euroleague players. Significant differences were found in peak PL for 30-s (p<.001, *moderate*) and 60-s (p=.02, *small*) time epoch, with higher values exhibited by the Euroleague players.

Discussion and conclusions

The aim of this study was to compare physical demands on two different teams playing at different levels using the same inertial devices. Notably, there are no previous studies that have investigated differences in external load between two elite basketball teams playing separate competitions. The main findings underscore that ACB/Euroleague competitions impose higher physical demands, as expressed in summarized variables like PL and the most demanding scenarios in epochs of 30 and 60 seconds. Understanding the external load is crucial for optimizing training strategies and player performance. Therefore, it is recommended that training staff and players carefully analyze the external load to tailor training programs effectively and enhance players' readiness and performance on the court.

PL variable revealed significantly higher physical demands during ACB/Euroleague games compared to ABA/Eurocup across all levels of intensity (total: ES=-1.54; band 2: ES=-2.31; band 3: ES=-1.96), respectively. Previous research investigating physical demands of various levels of basketball games has indicated that Division I or elite

Table1. Descriptive values (mean± standard deviation) and statistical comparisons in selected variables between both analyzed teams

Variables	**ABA-Eurocup (N=32)**		**ACB-Euroleague (N=18)**			
Average intensity (AU·min⁻¹)	M	SD	M	SD	p-value	Effect size
PlayerLoad™	8.44	1.45	10.70	1.45	<.001	-1.54
Player Load Band 2	3.70	0.82	5.52	0.70	<.001	-2.31
Player Load Band 3	1.40	0.57	3.07	1.16	<.001	-1.96
IMA Accel High	0.43	0.18	0.43	0.20	.795	-0.02
IMA Accel Low	1.71	0.64	1.50	0.57	<.001	0.34
IMA Accel Medium	0.62	0.24	0.53	0.25	<.001	0.34
IMA CoD Left Low	7.58	2.20	4.89	2.05	< .001	1.25
IMA CoD Left Medium	1.47	0.44	1.19	0.49	<.001	0.61
IMA CoD Left High	0.51	0.20	0.48	0.22	.095	0.15
IMA CoD Right Low	7.76	1.99	4.70	2.07	<.001	1.51
IMA CoD Right Medium	1.51	0.44	1.13	0.54	<.001	0.77
IMA CoD Right High	0.50	0.20	0.46	0.24	.043	0.19
IMA Decel Low	1.79	0.52	1.85	0.73	.356	-0.08
IMA Decel Medium	0.63	0.21	0.63	0.24	.854	-0.01
IMA Decel High	0.30	0.12	0.29	0.15	.263	0.10
IMA Jump Count Low Band	0.36	0.20	0.45	0.24	<.001	-0.39
IMA Jump Count Med Band	0.26	0.15	0.38	0.18	<.001	-0.78
IMA Jump Count High Band	0.23	0.12	0.22±	0.12	.389	0.08

Note. AU: arbitrary units, Accel: acceleration, CoD: change of direction, Decel: deceleration; SD: standard deviation.

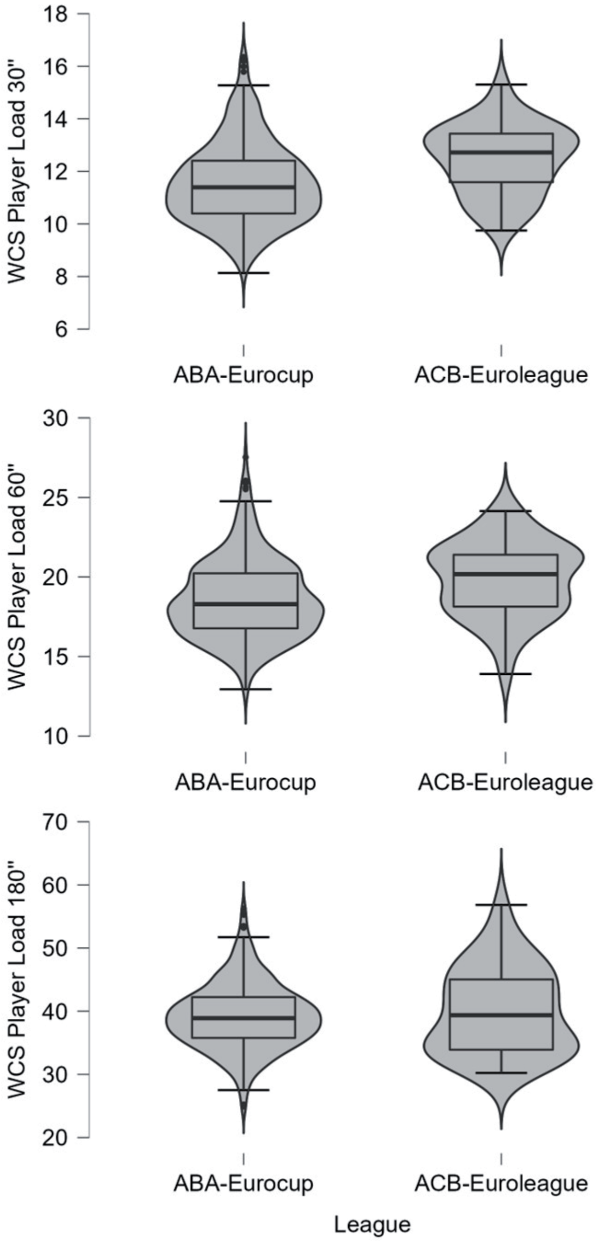

Figure 1. Peak intensities from both analyzed teams for PlayerLoad™ (AU·min⁻¹) variables in the three examined time epochs (30'', 60'' and 180'').

players engage in a greater number of high and mid-level activities compared to lower division players (Ferioli et al., 2020). It is important to note that the study highlighted differences between the demands on elite, semi-professional, and amateur basketball games, unlike ours, which specifically showcases disparities between the two European elite levels. Unlike our methodology, which utilized both inertial devices and time motion analysis, the prior study solely relied on time motion analysis, hence comparisons between the two techniques should be approached cautiously.

Moreover, previous research suggests that PL variable could serve as a sufficient guide for adjusting workload intensities for training sessions (Fox, et al., 2021). However, the substantial differences observed in PL variable, individual variables and in the most demanding scenarios between elite teams/leagues in our study diverge from this notion. These findings underscore that if such distinctions in external load exist among elite teams, general conclusions regarding basketball external load cannot solely rely on a single external load variable. Therefore, understanding these nuanced differences in external load between elite basketball teams is paramount for developing tailored training prescriptions that effectively optimize player performance and minimize the risk of injury.

In contrast to PL variable, IMA variables indicate that Eurocup/ABA team exhibited higher values for low and medium intensity acceleration and change of direction metrics (ES=0.34-1.51) compared to ACB/Euroleague team. These findings are in line with previous study with sub-elite and elite U18 players, which demonstrated that higher level of basketball games demand a reduced proportion of low and medium intensity actions (Trapero, et al., 2019). These results suggest two possible interpretations. First, the higher the level of the competition, the more selected and trained players are, promoting more informed decisions and more economized movement (Zhang, et al., 2017). Second, the variation in load demands is consequence of different playing styles in each league, indicating that each league or team may exhibit specific characteristics of physical demands. This implies that success in a particular league depends not only on individual basketball skills but also on the ability to withstand the physical demands associated with a certain style of basketball game. Furthermore, the Eurocup/ABA team showed larger values in low and medium level change of direction and acceleration actions, while the ACB/Euroleague team exhibited larger values in low and medium jump actions. This difference could be attributed to the variation in playing styles or the dominance of specific playing positions within each team's tactics. As previous studies have shown, different playing positions in basketball demand specific configuration of external load factors that contribute to their game, with change of direction being a primal component for guards and forwards and jumping being a primal component for centers (Salazar, et al., 2020). These findings underscore the significance of league-specific playing styles in influencing physical demands of basketball.

The results concerning the most demanding scenarios indicate that the Euroleague/ACB league demands higher frequency of external load when peak demands were measured in epochs of 30-s ($p<.001$, *moderate*) and 60-s ($p=.02$, *small*), but not in 180-s. This suggests that when a longer epoch was considered, external load seems similar, possibly due to the game rules or specific characteristics, while shorter epochs provided insights into the load demands during live basketball gameplay. Previous research suggests that traditional average results underestimate the peak physical demands that occur during the game, hence calculating the most demanding scenarios as rolling average was considered more suitable for describing these situations (Vázquez-Guerrero & Garcia, 2021). Furthermore, it is important to note that previous studies have demonstrated that most demanding scenarios fluctuate from quarter to quarter and between playing positions (Garcia et al., 2022), thus these results should be interpreted with caution.

Lastly, it is important to acknowledge several limitations. Firstly, the absence of internal load measures in this investigation suggests that the findings may not fully represent the physiological demands of basketball games. Future research may incorporate a holistic workload monitoring to provide a more comprehensive understanding of physical demands inherent in basketball gameplay. Secondly, the substantial differences in PL observed in our study may be attributed to disparities in game situation cutting. Even minor discrepancies in cutting actions can result in significant changes in PL variables, which are influenced by time dynamics (Garcia et al., 2022). Thirdly, we only analyzed a portion of the season rather than all games within a season, overlooking potential variations in external load demands across the season's progression, as previously noted in the literature (Conte, Kolb, Scanlan, & Santolamazza, 2018).

In conclusion, understanding the demands of a basketball game is crucial for effective training and performance optimization. This study contributes to this understanding by highlighting variations in external load variables among different teams and styles of play. The findings suggest that practitioners should rely on their own team's external load values for training load management, rather than attempting to adhere to standards established by external sources. Moreover, the results underscore the importance of contextual factors in explaining team-to-team differences in external load. Future studies should delve deeper into these contextual factors to unravel the mechanisms underlying such variations. In practice, it is recommended that practitioners use their team's external load data as a guiding principle during basketball practice planning, rather than relying on values obtained from other teams or external sources. By doing so, practitioners can tailor training regimens more effectively to meet the specific demands of their team's style of play and enhance overall performance.

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PACING STRATEGIES IN MEN'S AND WOMEN'S WORLD-RECORD MARATHON PERFORMANCES AND OLYMPIC GAMES AND WORLD CHAMPIONSHIP'S WINNING PERFORMANCES

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Abstract:

The aims of this study were to compare marathon pacing profiles between major championships winning races and world record (WR) races in men's and women's long-distance runners. Percentages of mean race speeds (%RS) for each 5 km section and last 2,195 m were compared between the latest 12 men's and 8 women's marathon WRs and the most recent 14 men's and 14 women's performances leading to either World Championship or Olympic Games (championships) gold medals, and between sexes in championships, through analysis of variance. Additionally, the coefficient of variation in pace (%CV) was compared through independent samples t-tests. %RS during the first 5 km was greater in WRs than championships in men ($p = 0.010$, $d = 1.07$), with a subsequent even pacing profile. More negative pacing profiles were adopted in championships than WRs in men ($p < 0.001$, $d = 2.07$). Women's WR and championship performances were characterized by even and negative pacing profiles, with different %CV ($p < 0.001$, $d = 1.89$). Whereas marathon WRs are characterized by fast, even and sustained paces, slower paces and more negative pacing approaches with fast endspurts are adopted during winning major championship performances. These fast endspurts are specially used by women in championships.

Keywords: *behavior, competition, endurance, running, tactics*

Introduction

An appropriate pacing strategy, defined as the regulation of exercise intensity and the way effort is distributed throughout an exercise task, is critical to achieving optimal performance by elite athletes (Foster, Schrager, Snyder, & Thompson, 1994). Pacing comprises a complex decision-making process that could be either beneficial or detrimental to individual performance (Renfree, Martin, Micklewright, & St Clair Gibson, 2014). Indeed, the specific problems faced by athletes in the competition are related to the distribution of available energy over a race (i.e., pacing behavior) and successful engagement in interpersonal competition (i.e., tactical ability) (Hanley, 2015) either when racing against the clock or against other competitors. Pacing and tactical behaviors have been found to be decisive factors in achieving high performance (Casado, Hanley, Jiménez-Reyes, & Renfree, 2021). More specifically, an optimized pacing strategy can improve performance in world-class marathoners (Angus, 2014). However, pacing behaviors differ according to the mode of exercise, event duration, knowledge and experience of the athlete and each opponent's physiological capacity (Casado, et al., 2021). In this regard, different pacing strategies are typically adopted by elite marathoners. Some of these profiles are negative, positive, and even pacing profiles (Casado, et al., 2021). A negative pacing profile is characterized by an increase in speed or power over the duration of the event. By contrast, a positive profile is characterized by a gradual decrease in speed or power throughout the duration of the event.

Contemporary marathon World Records (WRs) are characterized by a negative pacing pattern (Díaz, Fernández-Ozcorta, & Santos-Concejero, 2018), where the second half of the marathon is faster than the first. This is quite different from the "hitting the wall" pattern often seen in sub-elite runners, which is characterized by a decrease in speed from 35-38 km onwards due to the accumulated fatigue across the race (Muñoz-Pérez, Lago-Fuentes, Mecías-Calvo, & Casado, 2023). However, the pacing strategy adopted might be substantially different from that during major championship races. In championship races, the main objective is to achieve the best possible position. In regular competitions, such as big-city marathons, pacemakers are used to achieve the fastest possible winning performance during the event (Casado, et al., 2021). It is also important to choose wisely and join a running pack, adopting an initial non-excessive pace during the race to avoid a speed loss during its latest stages (Hanley, 2015). In addition, important sex-based differences in pacing strategy have been found during Olympic and World Athletics Championship marathons. Women typically slowed less during the race and were more likely to run a negative split than men (Hanley, 2016; Renfree & St Clair Gibson, 2013). Further, women's and men's marathoners have used an even or negative pacing profile, respectively, to break marathon WRs over the last 20 years (Díaz, Fernández-Ozcorta, Torres, & Santos-Concejero, 2019).

The differences between marathon pacing strategies during WR performances and major championships (i.e., World Championships and Olympic Games) have not been well studied. Better understanding of pacing during these major competitions could help athletes and coaches to optimize running strategies during different types of marathon races and to differentiate the training demands that are needed for the preparation of each type of race. Therefore, the aims of this study were twofold: to compare pacing profiles between: a) marathon major championships winning races (championships) and WR races in men and women, and 2) men and women in championships only, as this comparison was conducted previously in WRs (Díaz, et al., 2019). It was hypothesized that a slower pace with a faster endspurt (relative to the mean race pace) would be adopted during the championships vs. WR races. Additionally, a greater speed increase throughout the race was expected in women vs. men during championships.

Materials and methods

Design and data source

An observational design was carried out. Data were collected through a publicly accessible website (Association of Road Racing Statisticians [www.arrs.run website]), from which the official men's and women's marathon WRs were gathered. The official final and split times of championships were collected from the Hymans and Metrahazi database (Hymans, 2020) when available and from the World Athletics website (www.worldathletics.org [access date 10th October 2023]).

Methodology and participants

Twelve men's and eight women's marathon WRs, broken from 1998 to 2023, were analyzed. These eight women's WRs were paced by men's pacemakers. In turn, two other women's WRs were excluded from the analysis as they were not assisted by men's pacemakers. Regarding championships, 14 men's and 14 women's performances leading to either marathon World Championship or Olympic Games gold medals, achieved from 2001 to 2023, were analyzed. All WRs were performed between the 24th of September and until the 13th of April in the year they were achieved. By contrast, championships were held on dates between the 17th of July and until the 5th of October in their respective years. In addition, the unofficial sub-2 hours marathon performance achieved by Eliud Kipchoge in Vienna in October 2019 was also analyzed.

All section (i.e., split) times are defined both in terms of absolute speed ($m \cdot s^{-1}$) and as a percentage of the mean race speed (%RS). In addition, pace variation was analyzed using the coefficient of variation (%CV) of the race mean speed. For each athlete, the official final time and the time for each 5-km section were considered. The marathon distance was divided into eight sections of 5 km and a final, ninth, section of 2.195 km.

Statistical analysis

All data are presented as means and standard deviations (mean ± SD). Normal distribution and equality of variances were checked through the Shapiro-Wilk normality test and the Levene test, respectively. Assumption of sphericity was also checked through Mauchly's test, and Greenhouse-Geisser corrections were used if it was violated. Two-way analyses of variance (ANOVAs) with repeated measures with %RS as a between-section factor and sex (i.e., men or women) as a between-subjects factor were used to compare the pacing behavior between men and women in both WRs and championships. In addition, two-way repeated measures ANOVAs with absolute speed and %RS as a between-section factor and type of race (i.e., WR or championships) as a between-subjects factor were conducted to determine the pacing behaviors in the different race types. *Post-hoc* Tuckey corrections were performed in all pairwise comparisons, when justified by ANOVA. In addition, two independent samples *t*-tests were conducted to compare pacing strategies between WRs and championships in men and women, and between men's and women's championship- performances. An independent samples *t*-test was performed to compare %CV of pace between winning performances in championships and WRs in both sexes. Effect sizes were calculated through partial eta-squared for the repeated measures ANOVAs and Cohen's *d* (Cohen, 1988) for the Tukey *post-hoc* and *t*-student tests. Partial eta-squared was considered small (0.01), moderate (0.01–0.06) or large (> 0.15) (Cohen, 1988). Cohen's *d* was interpreted as small (≥ 0.2 and < 0.6), moderate (≥ 0.6 and < 1.2), large (≥ 1.2 and < 2.0) or very large (≥ 2.0 and < 4.0)((Hopkins, Marshall, Batterham, & Hanin, 2009)). The level of significance was defined at p<.05. IBM SPSS Statistics for Windows (Version 28.0 Armonk, NY: IBM Corp.) was used to analyze all data.

Results

Table 1 describes the section times of WRs analyzed in the present study. Table 2 describes the section times of the championships examined.

Figure 1 describes different pacing strategies adopted in the championship marathons and WRs among men and women in both % RS and absolute speed. Men's WRs were characterized by a faster first 5 km than those in championships (p=.01 *d*=1.07), with a subsequent even pacing profile during the rest of the race (Figure 1A). On the other hand, more negative pacing profiles were adopted during men's championships than men's WRs (Figure 1A and 1C). In this sense, %CV of the normalized speed was greater in men's championships than in WRs (2.91 ± 0.75 % vs. 1.52 ± 0.54%, p<.001 *d* = 2.07), showing that championship performance displayed a wider variation of pace. Men's WRs were run at a faster speed throughout the race than championships (Figure 1C).

Significant differences in normalized or absolute speed with at least moderate effect size between global championship winning performances and world records within each section are indicated as $^{\#}$ p<.05 with moderate effect; $^{\#\#}$ p<.05 with large effect; * p<.001 with moderate effect; ** p<.001 with large effect; *** p<.001 with very large effect. Significant variation across sections in women's global championship performances are indicated as & (p<.001 with small effect) and as $ in men's world records (p=.006 with small effect).

Women's WR and championship performances were characterized by even and negative pacing profiles, respectively (Figures 1B and 1D). Thus, championships also showed a wider variation of pace than WRs (%CV = 3.18 ± 0.88 % vs. 1.61 ± 0.72%, p<.001, *d* = 1.89). During the last 7.195 km, a faster normalized speed was observed in

Table 1. Final and section times of men's and women's marathon world records broken from 1998 to 2023

Athlete (men and women)	City and year	Final time (h:min:s)	Section (km) and speed (m/s)								
			0-5	*5-10*	*10-15*	*15-20*	*20-25*	*25-30*	*30-35*	*35-40*	*40-end*
R. da Costa	Berlin 1998	2:06:05	5.43	5.45	5.41	5.47	5.68	5.71	5.68	5.68	5.93
K. Khannouchi	Chicago 1999	2:05:42	5.50	5.64	5.62	5.64	5.51	5.56	5.69	5.55	5.73
K. Khannouchi	London 2002	2:05:38	5.66	5.60	5.57	5.57	5.70	5.61	5.57	5.48	5.67
P. Tergat	Berlin 2003	2:04:55	5.55	5.57	5.62	5.57	5.57	5.67	5.71	5.69	5.82
H. Gebrelassie	Berlin 2007	2:04:26	5.66	5.66	5.62	5.59	5.59	5.61	5.66	5.75	5.84
H. Gebrelassie	Berlin 2008	2:03:59	5.71	5.69	5.62	5.64	5.61	5.64	5.69	5.75	5.70
P. Makau	Berlin 2011	2:03:38	5.70	5.68	5.71	5.69	5.63	5.81	5.69	5.56	5.73
W. Kipsang	Berlin 2013	2:03:23	5.73	5.66	5.75	5.71	5.60	5.63	5.71	5.71	5.92
D. Kimetto	Berlin 2014	2:02:57	5.67	5.67	5.64	5.77	5.73	5.75	5.89	5.67	5.66
E. Kipchoge	Berlin 2018	2:01:39	5.79	5.70	5.70	5.81	5.76	5.81	5.83	5.75	5.98
E. Kipchoge	Berlin 2022	2:01:09	5.85	5.89	5.88	5.87	5.79	5.73	5.75	5.66	5.84
K. Kiptum	Chicago 2023	2:00:35	5.77	5.84	5.77	5.75	5.78	5.77	6.02	5.95	5.90
T. Loroupe	Rotterdam 1998	2:20:47	5.03	5.03	5.05	4.98	4.91	5.02	5.03	4.92	5.02
T. Loroupe	Berlin 1999	2:20:43	5.10	5.14	5.00	4.94	4.85	4.79	5.06	5.07	5.10
N. Takahashi	Berlin 2001	2:19:46	4.71	5.06	5.05	5.18	5.19	5.13	5.12	5.08	5.20
C. Ndereba	Chicago 2001	2:18:47	4.98	5.08	5.07	5.03	5.11	5.04	5.07	5.00	4.81
P. Radcliffe	Chicago 2002	2:17:18	5.05	5.12	5.11	5.10	5.17	5.18	5.18	5.09	5.10
P. Radcliffe	London 2003	2:15:25	5.27	5.14	5.13	5.14	5.18	5.20	5.22	5.24	5.28
B. Kosgei	Chicago 2019	2:14:04	5.39	5.21	5.22	5.20	5.18	5.29	5.23	5.22	5.31
T. Assefa	Berlin 2023	2:11:53	5.21	5.29	5.31	5.40	5.27	5.36	5.38	5.36	5.49

Table 2. Final and section times of women's and men's marathon global championship (World Championships [WCh] and Olympic Games [OG]) winning performances achieved from 2001 to 2023

Athlete (men and women)	City, type of race and year	Final time (h:min:s)	Section (km) and speed (m/s)								
			0-5	*5-10*	*10-15*	*15-20*	*20-25*	*25-30*	*30-35*	*35-40*	*40-end*
G. Abera	Edmonton WCh 2001	2:12:42	5.25	5.39	5.13	5.24	5.28	5.30	5.29	5.41	5.61
J. Gharib	Paris WCh 2003	2:08:31	5.52	5.46	5.43	5.24	5.37	5.41	5.66	5.62	5.69
J. Gharib	Helsinki WCh 2005	2:10:10	5.43	5.54	5.48	5.40	5.36	5.48	5.46	5.22	5.07
A. Kirui	Berlin WCh 2009	2:06:54	5.49	5.56	5.62	5.66	5.58	5.52	5.48	5.47	5.43
A. Kirui	Daegu WCh 2011	2:07:38	5.22	5.42	5.51	5.47	5.66	5.83	5.68	5.46	5.23
S. Kiprotich	London OG 2012	2:08:01	5.42	5.42	5.77	5.56	5.60	5.49	5.27	5.51	5.37
S. Kiprotich	Moscow WCh 2013	2:09:51	5.24	5.34	5.51	5.49	5.42	5.41	5.42	5.42	5.66
G. Ghebreslassie	Beijing WCh 2015	2:12:28	5.16	5.30	5.21	5.35	5.24	5.20	5.42	5.60	5.39
E. Kipchoge	Rio OG 2016	2:08:44	5.37	5.33	5.30	5.35	5.29	5.54	5.78	5.66	5.78
G. K. Kirui	London WCh 2017	2:08:27	5.21	5.34	5.43	5.45	5.76	5.65	5.66	5.41	5.34
L. Desisa	Doha WCh 2019	2:10:40	5.17	5.36	5.22	5.52	5.59	5.35	5.34	5.35	5.85
E. Kipchoge	Tokyo OG 2020	2:08:38	5.44	5.35	5.49	5.30	5.34	5.51	5.76	5.58	5.45
T. Tola	Eugene WCh 2022	2:05:36	5.30	5.50	5.55	5.56	5.45	5.57	5.88	5.89	6.00
V. Kiplangat	Budapest WCh 2023	2:08:53	5.35	5.54	5.36	5.40	5.39	5.50	5.69	5.56	5.21
L. Simon	Edmonton WCh 2001	2:26:01	4.63	4.82	4.68	4.82	5.01	4.60	4.91	4.99	5.08
C. Ndereba	Paris WCh 2003	2:23:55	4.81	4.92	4.88	4.72	4.75	4.78	4.97	5.22	5.10
P. Radcliffe	Helsinki WCh 2005	2:20:57	4.97	5.02	5.05	5.14	5.00	5.03	4.94	4.86	4.82
C. Ndereba	Osaka WCh 2007	2:30:37	4.49	4.66	4.61	4.60	4.57	4.72	4.71	4.78	5.23
X. Bai	Berlin WCh 2009	2:25:15	4.70	4.80	4.87	4.73	4.70	4.90	5.05	4.87	5.16
T. Gelana	London OG 2012	2:23:07	4.81	4.78	4.79	4.82	4.93	5.10	4.98	5.00	5.26
E. N. Kiplagat	Moscow WCh 2013	2:25:44	4.81	4.80	4.98	4.73	4.74	4.79	4.88	4.83	4.97
M. Dibaba	Beijing WCh 2015	2:27:35	4.66	4.72	4.67	4.64	4.64	4.74	4.84	5.03	5.26
J. J. Sumgong	Rio OG 2016	2:24:04	4.79	4.91	4.80	4.79	4.90	4.84	4.85	5.05	5.20
R. Chelimo	London WCh 2017	2:27:11	4.63	4.71	4.68	4.74	4.84	4.74	4.65	5.10	5.18
R. Chepngetich	Doha WCh 2019	2:32:43	4.54	4.53	4.82	4.49	4.52	4.58	4.59	4.77	4.66
P. Jepchirchir	Tokyo OG 2020	2:27:20	4.62	4.57	4.75	4.72	4.79	4.84	4.93	4.90	4.98
G. Gebresalase	Eugene WCh 2022	2:18:11	5.15	5.06	4.95	5.17	5.06	5.18	5.04	5.02	5.30
A.B. Shankule	Budapest WCh 2023	2:24:23	4.66	4.72	4.79	4.72	4.83	5.02	5.17	5.13	4.85

championships than in WRs (Figure 1B). Women's WRs were faster than championships during every section apart from the last 2.195 km (Figure 1D). Moreover, women's championship performances were faster during the last 2.195 km than the first 5 km ($p<.001$).

Figure 2A describes the percentage of normalized speed during each section of men's and women's championship marathon performances. Although both men's and women's championship marathoners displayed an even pace during most of the race, women were able to generate a relatively faster endspurt than men ($p=.029$, $d = 0.62$).

Both men's (Figure 2B) and women's (Figure 2C) normalized speeds (%) during each section and finishing times of the current marathon WRs and Tokyo 2020 Olympic Games are indicated in Figure 2. Additionally, normalized speeds (%) during each section and finishing time of the only marathon performance covered in less than two hours are indicated in Figure 2B. Kenyan runner Kelvin Kiptum adopted an even pacing strategy with a fast endspurt from the 30th to the 35th km of the race to break the current WR by the time of writing (Figure 2B). Furthermore, the strategy to break the two hours barrier during an unofficial race by the

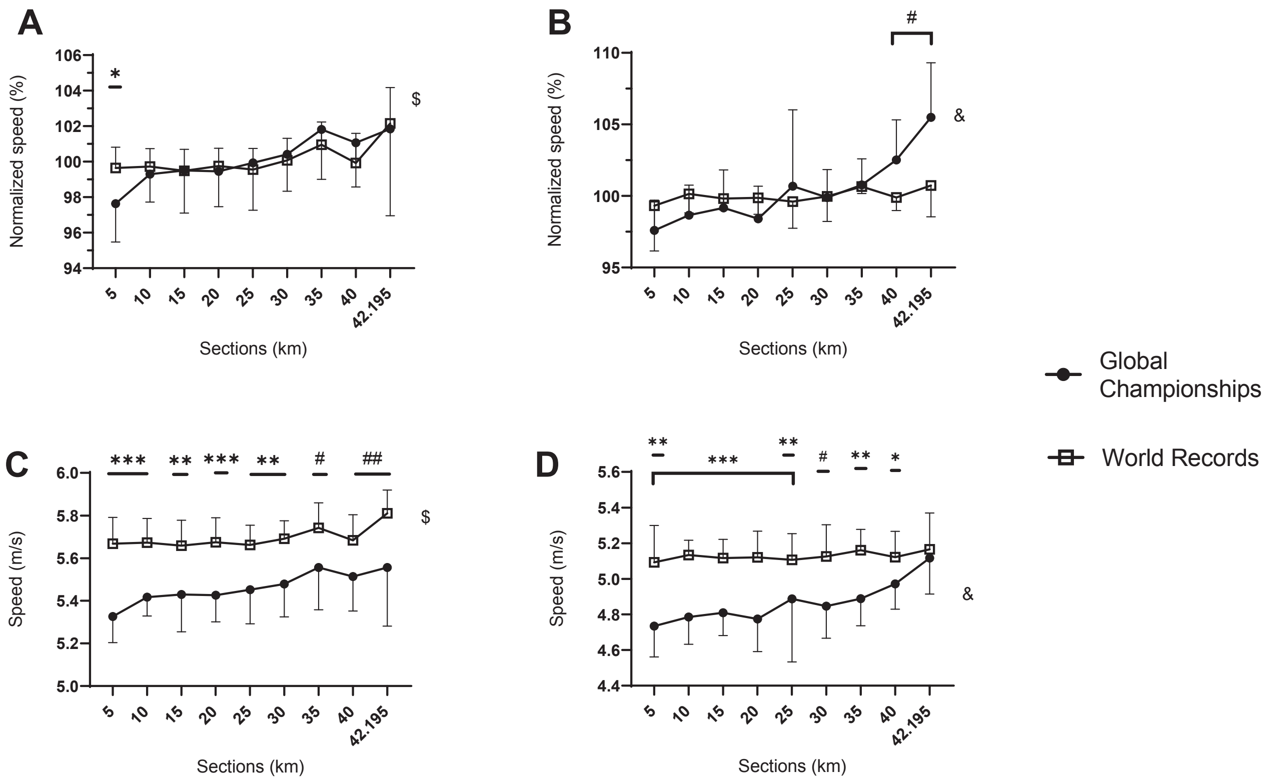

Figure 1. Differences in marathon normalized mean speed and absolute mean speed within each race section between global championship winning performances and world records in men (A and C) and women (B and D) and pace variation across sections in each type of race.

Kenyan Eliud Kipchoge, was even more even than that used to break the current WR, and also was characterized by an endspurt (Figure 2B). However, Kipchoge displayed greater fluctuations of speeds with a remarkable acceleration from the 25th to the 35th km to break away from the field and win the Tokyo 2020 Olympic Games marathon (Figure 2B). Negative and even pacing profiles characterized women's performances at the Tokyo 2020 Olympic Games by Kenyan runner Peres Jepchirchir and the current marathon WR set in the Berlin Marathon 2023 by the Ethiopian Tigist Assefa, respectively (Figure 2C).

Discussion and conclusions

The main aims of the present study were to compare recent championships (World Athletics Championships and Olympic Games) and WR marathon pacing strategies in men and women and to do so between sexes during championship performances. This is the first study directly comparing marathon pacing strategies between WRs and performances achieved during major championships. In agreement with our hypothesis, a more negative profile was displayed in championships than in WRs in both men and women. In this regard, the current data suggest that contemporary elite-standard marathons are more similar to long distance track races than to those covered by recreational runners which are characterized by a progressively slowing pace (e.g., hitting the wall) (Smyth, 2021).

The fact that none of the WRs analyzed were set during any major recent championship race (Tables 1 and 2) agrees with some of the present findings. For example, during the latest stages of WRs, when pacemakers cannot help WR performers because they have dropped out of the race, the absolute speed was similar and faster than that in championships in women (Figure 1D) and men (Figure 1C), respectively. That means that even despite having run much slower than WRs during almost the whole race (Figures 1C and 1D) and having to be as fast as possible during the last endspurt to win (Hanley, 2016; Renfree & St Clair Gibson, 2013), women's championship marathoners were not able to run faster than their counterparts breaking a WR during the last 2.195 km (Figure 1D), and men's championship runners did so even slower (Figure 1C). Therefore, these important speed differences among these types of races cannot only be explained by the different runners' aims or goals at each type of race (i.e., achieving the fastest mean speed during WRs vs. the highest finishing position during championships [Casado, et al., 2021]). Rather, the phenomenon explaining these differences should be considered multifactorial and is determined by several variables such as weather, the

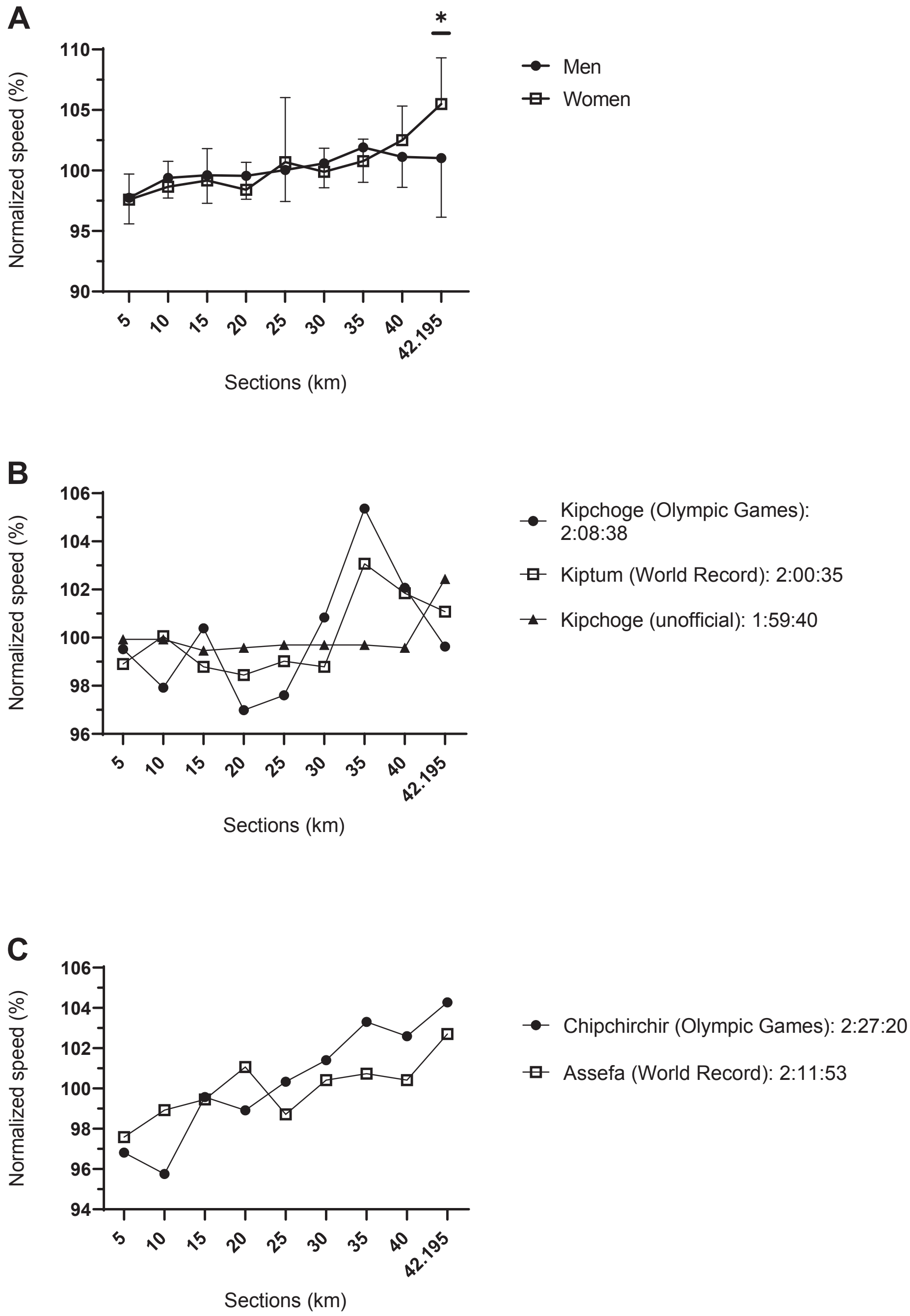

*Figure 2. Mean and standard deviation of normalized speed in men's and women's winning performances during the different sections of global championship marathons (A), and final times indicated as h:min:s and normalized speeds at each section of marathon Tokyo 2020 Olympic gold performances (Eliud Kipchoge [B] and Peres Jepchirchir [C]), current marathon world records (Kelvin Kiptum [B] and Tigist Assefa [C]) at the time of writing, and sub 2-hours race performed in Vienna 2019 (Kipchoge [B]). * Significant difference (p<.05) with moderate effect between sexes.*

help provided by pacemakers, runners' objectives, and course elevation. First, major championships are typically held during the warmest months of the year excepting some other 'hot' and 'humid' countries like Brazil or Qatar where these characteristics remain constant all year round. For example, very high temperatures and humidity were considered the major causes of marathon performance deterioration during the 2019 Doha World Championships in the women's race. In addition, 41% of the women's athletes taking part in this race did not finish, presumably due to weather issues (Beal, Corbett, Davis, & Barwood, 2022). In this sense, this negative influence of heat on marathon running performance leads to a greater slowing (Beal, et al., 2022) compared to cooler conditions might rely on thermoregulatory disturbances such as increased pulmonary ventilation and cardiovascular strain, and alterations in brain function, muscle metabolism and central fatigue (Gonzalez-Alonso, 2007; Nybo, Rasmussen, & Sawka, 2014). All WRs analyzed have been broken during the autumn (fall), winter or spring at the locations where those races were held.

On the other hand, pacing behaviors can also be impacted by drafting. Drafting influences positively on performance in distance running events (Casado, Moreno-Pérez, Larrosa, & Renfree, 2019). Accordingly, a reduction of almost 5.9% in the metabolic cost of running could be derived from running behind another athlete during the second half of a marathon (Hoogkamer, Snyder, & Arellano, 2018). The specific influence of drafting is particularly important during WR performances, in contrast to championships. They are typically assisted by pacemakers who are expected to set a preassigned pace near the anticipated limit of the best runners throughout the race (Hanley, 2016). Therefore, apart from the faster absolute overall speed in WRs than in championships, the assistance provided by pacemakers could also partially explain the faster percentage of normalized speed during the first 5 km of WR races in men and the more even pacing profile set by men and women in WRs vs. championship marathons. It also may explain the greater performance and more even pacing strategy in the only (unofficial) marathon run covered under two hours and the current men's WR (Figure 2B), being achieved by Kipchoge and Kiptum, respectively. These differences may mainly be explained by the assistance of rotating pacemakers in the former until almost the end the race. The other important factor that could differentiate the pacing profile observed within each type of race is the distinct goal of the athlete. Whereas championship runners usually establish a slow pace during the early stages to ultimately be able to generate a fast endspurt and achieve the highest finishing position, WR contenders prefer to adopt the evenest pace throughout the race to achieve the fastest mean speed (Díaz, et al., 2019). Furthermore, Casado, Ranieri, Hanley, Foster, & González-Mohíno (2024) found similar pacing trends in middle-and long-distance track WRs, and Olympic and World Championship medal performances, displaying more even and negative pacing profiles, respectively.

Further, in agreement with our hypothesis, women's championship races displayed a more negative pacing behavior than men's championship races did (Figure 2A). Accordingly, women's championships were characterized by the completion of a prolonged, fast endspurt. These outcomes support those of Hanley (2016), who reported that whereas women's Olympic Games and World Championship marathon medalists did not slow down during the later stages of the race, their male counterparts did. However, in contrast to the present study, Hanley (2016) did not directly compare pacing behaviors between sexes. Furthermore, the faster percentage of normalized speed displayed by women in championships between the final 2.195 km and the first 5 km also emphasizes the negative profile performed by these athletes.

Differences in pacing strategies between sexes might depend on physiological, hormonal, and decision-making factors (Deaner, Carter, Joyner, & Hunter, 2014). Indeed, whereas men are more susceptible to glycogen depletion, which can contribute to a considerable slowing and greater fatigue, women display a lower and greater rate of carbohydrate and amino acid, and fat oxidation, respectively, during submaximal endurance exercise than men (Rapoport, 2010). These differences might be caused by 17-β-estradiol in women (Tarnopolsky, 2008).

Additionally, women possess a greater proportional area of 'slow' type I fibers, which are more resistant to fatigue, especially in long-duration exercise, in several muscles that are essential for locomotion (Hunter, 2014). Studies of non-elite runners suggest that men are more likely to slow their marathon pace than women (Deaner, et al., 2014). Therefore, the combination of these factors could confer women greater physiological, hormonal, and tactical abilities that could allow them to generate a relatively faster and prolonged endspurt during the latest stages of the race (Figure 2A).

Pacing behaviors leading to both current men's and women's Olympic marathon gold medals displayed a greater variation of pace than those leading to current men's and women's marathon WRs (Figure 2B and 2C). Similarly, Foster, De Koning, & Thiel (2014) found that the faster the mile world records, the lower the variability in pacing behavior (Foster, et al., 2014). However, whereas both WRs adopted an even pacing strategy with a fast endspurt, reigning men's Olympic champion Eliud Kipchoge (at the time of writing) slowed during the final stages of the race to earn his gold medal, although he had a very fast mid-race 10-km to break away from the field. The reigning women's Olympic champion Peres Jepchirchir generated a fast endspurt to win her Championship (Figure 2B and 2C). These endspurts observed during both WRs, the sub-two hours marathon performance, and championships could be partially explained by the assistance of the use of new shoe technology based on specifically positioned carbon fiber plate and foam cushioning (Muniz-Pardos, et al., 2021), which showed improvements in both performance and running economy (Hébert-Losier, et al., 2022). The use of this technology might decrease muscular fatigue throughout the marathon (Muniz-Pardos, et al., 2021), and therefore contribute to the fast speeds achieved during the later stages. In addition, the ability to accelerate until the finish line after covering more than 35 km at a sustained and relatively fast speed might be explained by the development of the specific physiological determinants in this type of long endurance race. In this way, Jones et al. (2021) found that the only marathoner who had been able to run 42.195 km in under 2 hours until the time of writing the present article, Eliud Kipchoge, displayed remarkable values of running economy (Jones, et al., 2021) (i.e., energy cost at a submaximal and constant intensity (Foster & Lucia, 2007). Furthermore, durability (i.e., the time of onset and magnitude of deterioration in physiological-profiling characteristics over time during a prolonged exercise) has been recently considered as one of the endurance physiological performance determinants, especially in longer events such as the marathon (Maunder, Seiler, Mildenhall, Kilding, & Plews, 2021). Therefore, high levels of both running economy and durability may be behind of these remarkable marathon performances and their typical endspurts.

Championship racing featured a more negative pacing profile than that followed by WRs in men and women. Women's championship races displayed a more negative pacing profile than the men's equivalent races. In this sense, women's championships involved a prolonged and fast endspurt during the later stages of the race. Performances by current men's and women's marathon Olympic and World Championship gold medalists displayed a greater pace variation than that of the current men's and women's WRs at the time of writing. WRs were faster than championships across the whole race in both men and women. These differences could be related to the fact that most WRs were set during cooler months than those when championships were held, and to the benefits of pacemakers during WRs.

One limitation should be acknowledged in the present study. Pacing characteristics were analyzed using five km split times, which are too long and thus cannot fully explain the pacing behavior adopted by runners across the whole marathon.

Practical applications

Breaking a marathon WR requires the adoption of a basically even pace, avoiding, as much as possible, variation of pace across the race. In this sense, the initial speed of pacemakers during the race should be very carefully selected according to the specific abilities of the WR contender (i.e., performance in recent races and training performance during recent training sessions) and the specific time target which is dependent on the current WR. Excessively fast early paces may result in a further slowing that would prevent optimal performance and, therefore, prevent achieving a WR. In addition, climate conditions and course profile should be optimal to break a marathon WR. In effect, minimal changes in course elevation are required and air temperatures between 13°C and 18°C (Scheer, et al., 2021). On the other hand, marathon training specifically designed to be able to perform a negative pacing strategy might be necessary to win a championship marathon such as at the Olympic Games or World Athletics Championships. However, whereas women might need to develop the ability to generate a very fast and prolonged endspurt, men seem to be required to sustain a fairly fast pace from halfway onwards. These different abilities needed may in turn be optimally developed through different training approaches according to sex.

Future perspectives

Future studies could focus on the analysis of different psychophysiological responses to training and racing between men's and women's elite marathoners, which in turn could explain their different pacing behaviors during these world-class races. In addition, future studies should try to assess the pack formations typically adopted during marathon WRs, and not only during championships (Hanley, 2016), which may elucidate the differences in pacing behavior between men and women. Finally, future research could try to determine whether training strategies in elite marathoners that specifically target adaptations to achieve a negative pacing profile are more effective than those targeting the achievement of the fastest mean speed across the race, and vice versa.

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ARE AEROBIC CAPACITY, ANAEROBIC THRESHOLD, AND RESPIRATORY COMPENSATION VALUES DETERMINANTS FOR THE TIME OF USEFUL CONSCIOUSNESS AT 25000 FEET?

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Abstract:

The higher the altitude, the higher the risk of hypoxia exposure. Good fitness status or aerobic capacity (AC) of persons with the military or civil aviation sector and those interested in high-altitude sports have been thought of great importance to encounter hypoxic risk. It is unclear whether a difference in maximal oxygen consumption (VO_{2max}) capacity would result in differential tolerance in hypoxia responses. The present study aims to determine the relationship between AC, anaerobic threshold (AT), respiratory compensation (RC), and time of useful consciousness (TUC) of people working in the military or civil aviation sector and those interested in high-altitude sports. Eighty-seven healthy males were recruited on a volunteer basis (age = 24.2 ± 1.6 years; height = 177.0 ± 5.1 cm; weight = 76.4 ± 8.1 kg). The 25000 feet test was applied to the participants in the hypobaric chamber. During the test, participants' TUC levels were recorded. The Bruce protocol was used for the VO_{2max} test, and the maximal oxygen consumption value, AT, and RC regions were recorded. Participants were divided into four groups according to their VO_{2max} values. AT and RC values were higher in the group with high VO_{2max}, although not significant ($p>.05$). There was no statistically significant difference between the TUC levels of the groups. There was no statistically significant difference between the groups' TUC level, peripheral oxygen saturation (SpO_2), and heart rate levels ($p>.05$). The results clearly show that there is no significant relationship between VO_{2max} determined on the treadmill with a gas analyzer and TUC determined in the hypobaric chamber at 25000 feet. For future studies, the relationship between anaerobic capacity and hypoxia or studies in which different physical and physiological characteristics are evaluated together in the same participants may contribute to the literature.

Keywords: *effective performance time, oxygen consumption, hypoxia, aviation*

Introduction

In aviation and sports branches such as mountaineering-related to altitude, hypoxic effects begin to be observed gradually with the increase in altitude. Although it is more common in aviation in cases such as cabin pressure loss or oxygen systems failure, hypoxia can also be encountered in non-cabin pressure less aircraft (helicopters, etc.) operating at medium altitudes or in parachute jumps for sportive and military purposes. Hypoxia is defined as the insufficient partial pressure of oxygen to body tissues, the low atmospheric pressures, which generates a variety of physical, physiological, and psychological responses in humans (Smith, 2008). Especially, the effects may cause negative and undesirable situations in critical decision-making processes in central nervous system (CNS) (Heratika, et al., 2020; Petrassi, Hodkinson, Walters, & Gaydos, 2012; Sullivan-Kwantes, Cramer, Bouak, & Goodman, 2022). Time of useful consciousness (TUC) is defined as the time elapsed between additional oxygen loss and performance failure and is frequently used in the evaluation of decision-making in the CNS. TUC is also defined as the length of time in which a pilot can perform flying duties efficiently in an environment of inadequate oxygen supply and is based on time left until unconsciousness occurs, e.g., the TUC at 25000 feet is approximately 3-5 minutes (DeHart & Davis, 2002). In other words, if arterial and tissue deoxygenation does not stabilize, brain function progressively declines, which occurs exponentially at a very low partial arterial oxygen pressure (PIO2) The initial phase is referred to as the TUC and is the duration of effective and safe performance of operational tasks, which is followed by mental confusion and unconsciousness (Hall, 1949; Hoffman, Clark, & Brown, 1946). Effective performance time (EPT) or TUC at that altitude is a function of circulation time. Exercise of even modest levels shortens the EPT due to decreased circulation time and increased peripheral demand resulting in a faster loss of oxygen (Davis, Johnson, & Stepanek, 2008). Hypoxia impairs a spectrum of cognitive domains as previously described in the narrative (Petrassi, et al., 2012; Taylor, Watkins, Marshall, Dascombe, & Foster, 2016; Yan, 2014) and systematic reviews (McMorris, Hale, Barwood, Costello, & Corbett, 2017). Both simple (e.g., simple and choice reaction speed) and complex (e.g., processing speed, working memory, short-term memory, attention, executive function, and novel task learning) tasks are negatively affected by hypoxia, the degree of which can vary greatly between individuals (McMorris, 2017; Shaw, Cabre, & Gant, 2021). TUC duration is affected by many individual and environmental factors apart from altitude. TUC values are based on data that represent average values and reflect wide variation among individuals in time to incapacitation. This variation results from differences in an individual's total surface area for gas exchange in the lungs, total amount of hemoglobin available in the blood to bind oxygen, and oxygen consumption rate at rest (related to body mass index). Other sources of variation are the extent to which hypoxia stimulates increases in depth and rate of breathing and increases in the amount of blood the heart pumps (faster heart rate). Finally, individuals able to increase the amount of oxygen they can extract from the blood in muscle and brain tissue are more hypoxia-tolerant (Self, Mandella, White, & Burian, 2013).

Aerobic performance is a particularly appropriate performance trait in hypoxia at high altitudes, as aerobic metabolism is critical for staying active and maintaining movement in the cold (Cheviron, Bachman, Connaty, McClelland, & Storz, 2012; Hayes & O'Connor, 1999). Because hypoxia is both inevitable and persistent at high altitudes, some short-term mechanisms (e.g., metabolic depression, anaerobic metabolism) to cope with O2 deprivation have limited efficacy and the ability to maintain aerobic metabolism is critically important. However, hypoxia can have debilitating effects on aerobic performance, which can limit locomotor activity or impair thermogenesis, causing hypothermia (McClelland & Scott, 2019). Traditional aerobic-based training in hypoxia has received much attention. This method improves oxygen-carrying capacity by increasing erythropoietin secretion and hemoglobin mass and increases VO2max, anaerobic threshold (AT), bringing improvements to exercise performance (Ramos-Campo, et al., 2018). Both the heart and blood vessels respond to exercise in a variety of ways. AT and respiratory compensation (RC) values are important indicators of the degree of aerobic capacity (AC) (Fox, Bowers, & Foss, 1993; McArdle, Katch, F.I., & Katch, V.L., 2010). At the same time, the test using a gas analyzer, which is considered the gold determination standard of AC, is an indicator of cardiovascular endurance (Poole & Jones, 2017). AT and RC points can also be determined during the VO2max test (Jamnick, Botella, Pyne, & Bishop, 2018).

In the literature review, no study was found regarding the comparison of VO_{2max}, AT, and RC, on the one hand, and TUC value at 25000 feet, on the other, in a hypobaric chamber. The present study aims to determine whether there is a significant difference in TUC at 25000 feet in a hypobaric chamber between groups categorized according to AC, AT, and RC values in healthy men. According to the results of this study, the importance of improving aerobic characteristics, AT and RC values of people working in the civil and military aviation sector and those who are interested in high-altitude sports will be determined in terms of TUC.

Methods

Participants

Ninety-one healthy men were recruited on a volunteer basis from the military and civil aviation sector and those interested in high-altitude sports (mountaineering and climbing, parachuting). Four participants dropped out from the current study due to busy schedules. The final sample comprised eighty-seven individuals. Subjects were divided based on their VO_{2max} capacities according to Heyward (1997) protocol: excellent (46.5-52.4 $ml.kg^{-1}.min^{-1}$), good (42.5-46.4 $ml.kg^{-1}.min^{-1}$), fair (36.5-42.4 $ml.kg^{-1}.min^{-1}$), and poor (33.0-36.4 $ml.kg^{-1}.min^{-1}$). Four different groups were created with the participants according to their VO_{2max} capacity (Group 1: n=24, 24.0±1.6 years, 176.3±5.1 cm, 73.8±7.9 kg, BMI 23.8±2.5 $kg.m^{-2}$, body fat 16.6±4.3 %, VO_{2max} 49.4±2.6 $ml.kg^{-1}.min^{-1}$; Group 2: n=24, 24.1±1.2 years, 176.1±5.8 cm, 75.9±8.6 kg, BMI 24.5±2.3 $kg.m^{-2}$, body fat 18.8±4.3 %, VO_{2max} 40.0±1.1 $ml.kg^{-1}.min^{-1}$; Group 3: n =22, 24.3±1.7 years, 177.0±5.3 cm, 78.0±7.7 kg, BMI 24.9±2.0 $kg.m^{-2}$, body fat 21.8±3.7 %, VO_{2max} 43.5±1.4 $ml.kg^{-1}.min^{-1}$; Group 4: n =17, 24.3±1.7 years, 177.0±5.3 cm, 78.0±7.7 kg, BMI 24.9±2.0 $kg.m^{-2}$, body fat 21.8±3.7 %, VO_{2max} 34.2±1.8 $ml.kg^{-1}.min^{-1}$). All participants reported to be free from illness and injury in the last six months and medical drugs usage in the past week before the experiments took place. Signed informed consent was obtained from all participants. The study included men aged between

20-29 years, who had no known health problems and signed the voluntary consent form. The experiments were approved by the Eskişehir Technical University Research Ethics Committee (approved date July 5, 2022, under the number E-8914409-050.06.04-79145).

Study design

The explanatory consent form was signed by the participants on the first day of the study. Data collection for each participant occurred on the weekday during the morning hours (i.e., from 09:00 a.m. to 12:00 p.m.). Moderate water consumption was allowed for each volunteer during the tests. The participants were warned not to perform any physical activity the day before the tests and not to use stimulants such as food and medicine or coffee for two hours before the test hours. The researchers conducted the tests in groups of 5-6 subjects. Two days were allocated for the measurements. Anthropometric measurements and a hypobaric chamber test were applied on the first day. The height, weight, and fat percentage of the participants were recorded. Hypobaric chamber test measurements were performed in a quiet and air-conditioned (temperature 17-18°C, humidity 55-58%) room. The 25000 feet test was applied to the participants in the custom-made hypobaric chamber. During the test, participants' TUC durations were recorded. Participants were allowed to inhale 100% O_2 for 30 minutes at ground level for denitrogenation. At the end of this period, they were brought to the atmospheric conditions at an altitude of 25000 feet in 10 minutes. 100% O_2 support was cut off and the O_2 rate in the atmosphere was brought to 21%. From this moment onwards, the participants began their TUC period. O_2 saturation was monitored with a pulse oximetry device and the test was terminated when O_2 saturation fell below 70% or voluntarily when the person felt unwell. The TUC time of each participant was recorded separately.

On the second day, the Bruce protocol was used for the maximal oxygen consumption test (temperature 22-24°C, humidity 33-45%), and the VO_{2max} value, anaerobic threshold, and respiratory threshold regions were recorded.

Instrumentation and data collection

Measurement of body composition. The height of the participants was measured as recommended by the International Society for the Advancement of Kinanthropometry (ISAK) and with a 1/10 cm sensitivity (Holtain Harpenden 601, Holtain Ltd., UK). The body mass of the participants was measured with a scale of 1/10 kg using the scale model of the InBody brand 270 models (Biospace Co., S. Korea) body analyzer. To obtain the body mass index (BMI) values of the participants InBody brand 270 models (Biospace Co., S. Korea) body analyzer was used, and measurements were performed according to the procedure specified in the device manual. The data obtained were recorded in % (Alparslan, Arabacı, Güngör, Şenol, & Küçük, 2022).

Determination of maximal oxygen uptake (Bruce Protocol). The treadmill test with the gas analyzer is accepted as the gold standard for the determination of aerobic endurance and maximal oxygen consumption. The Bruce protocol (h/p/cosmos quasar med 170-190/65, h/p/cosmos & medical GMBH, Germany) was performed. The staged protocol began at 1.7 mph at 10% grade with increasing work rate (speed and grade) every 3-minutes until VO_{2max} was reached. Expired gas fractions (oxygen and carbon dioxide) were collected at the mouth and analyzed with a metabolic cart (Cosmed Quark CPED metabolic cart, Roma, IT). Measurements were processed in Omnia-Standalone software for Microsoft Windows version 1.4. The criteria for VO_{2max} were predetermined as two of the following: if there was a plateau in oxygen consumption despite an increased work ($\pm$ 2 $ml.kg^{-1}.min^{-1}$); the respiratory exchange ratio of >1.10; and a heart rate within ten beats of age-predicted maximum (220-age). Bruce protocol was applied after a 10-minute warm-up period. The gas analyzer system was calibrated before each test using the manufacturer's recommendations. While determining VO_{2max}, the data were analyzed by taking the average values in 15-second time intervals. In the threshold calculations, a new data group created by taking the average values of the data for 5 seconds was used. RC was determined by the V-slope method. This method is an algorithm in which VCO_2 is evaluated with VO_2 data (Ekkekakis, Thome, Petruzzello, & Hall, 2008).

Hypobaric chamber test. In the hypobaric chamber (Hypobaric Chamber-103435 Environmental Tectonic Crop, USA), a flight helmet and a flight mask were attached to the participants to isolate them from the external atmosphere. During the test, observers were present on the control panel both inside and outside the cabin. Inner observers and survey participants were not left above 18000 feet for more than 30 minutes. During the adjustment of the masks to the face, the oxygen equipment, and interphone controls, the participants wore masks, and the regulators were adjusted to the 100% oxygen position. For ear and sinus control, the height was increased to 7500 feet and returned to ground level in a 1-minute without exceeding 7500 feet. The 30-minute denitrogenation period was completed before the ascent to the altitude to be tested. 25000 feet were climbed by 5000 feet per minute. After the consciousness time limits were determined for the participants at 25000 feet, oxygen was re-administered to 100% and the participants were checked. Return to ground level was done at 2500 feet per

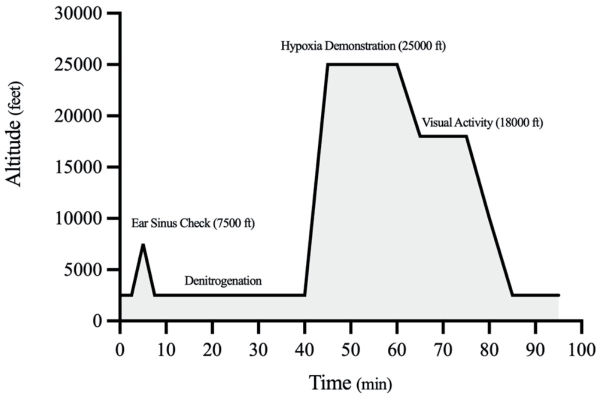


Figure 1. Hypobaric chamber flight profile.

minute (Sucipta, Adi, & Kaunang, 2018).

Criteria for TUC determination. The decision to determine the end point of a subject's time of TUC while undergoing high-altitude chamber training was at the discretion of the supervising flight physician. The decision was based on the physician's assessment skills as it pertained to the subject. The assessment was most often based on subjective findings by the subject as well as deterioration in neurocognitive functioning. The following criteria were utilized by the supervising physician for TUC determination: (i) any combination of three signs or symptoms noted by the subject, (ii) the presence of significant cyanosis, (iii) any disturbance in speech, (iv) loss of short-term memory and delay in communications, (v) incorrect response to a simple command, (vi) significant euphoria, (vii) significant mistake in flight controls of the simulator, (viii) tremor, (ix) staring (glassy-eyed), and (x) fixation. The presence of any of the above observations or combinations determined the end point of TUC and resulted in the immediate donning of the mask (Cipova, 2014).

Heart rate and oximeter device and data collection and analyses. Heart rate and oxygen saturation level were measured with a pulse oximeter device (ITAM-BlueECG-204P-Poland). Participants were evaluated and observed by an aerospace medicine specialist before, during, and after the test. Maximum HR was needed to determine the physiological parameters of the change in heart rate (HR) associated with the new ascent-based TUC. The maximum heart rate per subject and maximum heart rate per all subjects were collected from the Oximeter Report. The maximum heart rate per subject was compared to a heart rate at rest of a Cardiac Pulse Index (CPI). The lowest peripheral oxygen saturation (SpO_2) levels were collected from the Oximeter Report to determine the physiological parameters of oxygen saturation associated with the ascent-based TUC (every 10-second oximeter readout of the data from 5000 feet to donning mask was collected).

Statistical analyses

In the current research, descriptive statistics (mean, SD) were used for the description and explanation of data (TUC, lowest SpO_2 levels, net change CPI, physical characteristics, and VO_{2max}, AT, RC). The Kolmogorov-Smirnov test was used for investigating the normality of the data distribution. One-way analysis of variance (ANOVA) was calculated to compare anaerobic threshold, respiratory threshold, VO_{2max}, and TUC time values between the groups, the Bonferroni test for pairwise comparisons, and Cohen's d value for effect size was calculated. Pearson correlation test was used for the relationship between TUC duration and VO_{2max} value. Effect size Cohen's d-value was calculated; this value was considered small (0.20), medium (0.50), or large (0.80). All calculations were performed with SPSS version 26, statistical software (SPSS Inc., Chicago, IL, USA) and the significance level was determined as $p<.05$.

Results

Descriptive data regarding age, height, weight, BMI, body fat (%), TUC (sec), VO_{2max} ($ml.kg^{-1}.min^{-1}$), AT (sec), and RC (sec) for the groups are presented in Table 1. AT and RC times, TUC, and VO_{2max} levels of the groups by performance are presented in Figure 2. A-D, respectively. The change in HR and SpO_2 in the hypobaric chamber test and the threshold values in the AC test of G1, G2, G3, and G4 are presented in Figure 3. The comparison of TUC times of the groups separated by aerobic performance is presented in Figure 4. The relationship between the participants' anaerobic threshold and respiratory threshold values with TUC is presented in Table 2.

When the demographic data of the groups were compared, there was no statistical difference in terms of age, height, weight, and BMI ($p>.05$) (Table 1). In the between-groups comparison, body fat (%) in the G1 group was significantly lower than in the G4 group ($p<.05$).

Figure 2A-D shows TUC level of G1 (195.9±39.3), G2 (202.0±47.9), G3 (193.6±38.0), and G4 (191.5±42.3) ($p>0.05$). Also, the G1 group displayed higher VO_{2max} ($ml.kg^{-1}.min^{-1}$) values than the other groups. The AT and RC values were consistently higher, although the difference was not always statistically significant in the G1 group compared with the other groups ($p>.05$).

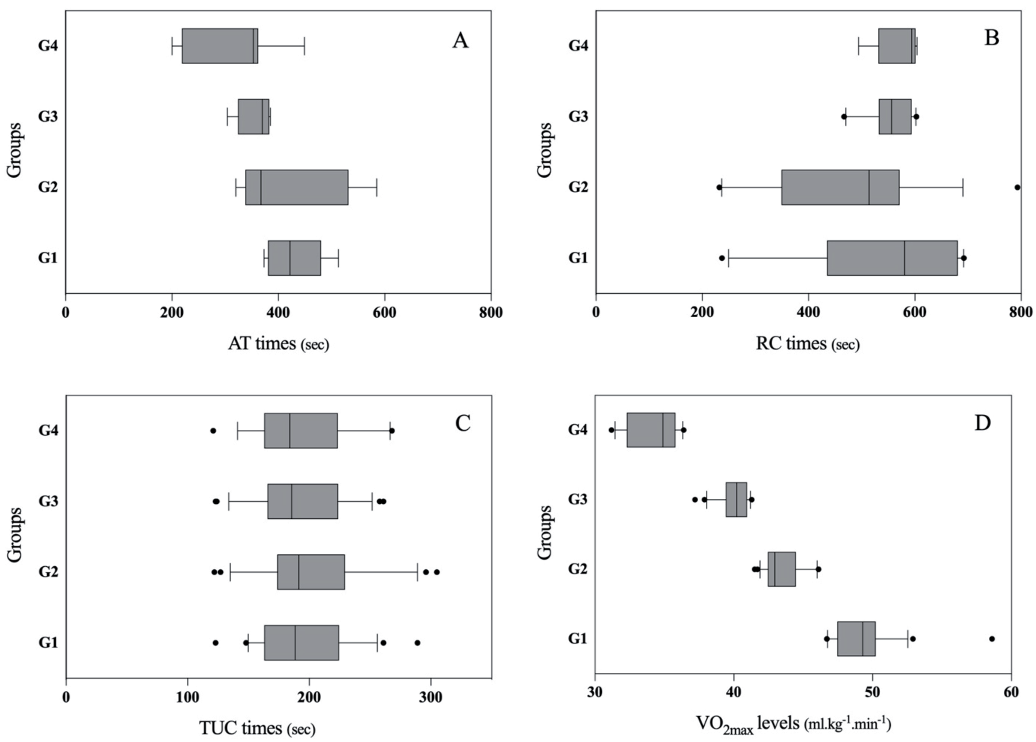
As seen in Figure 3, there was no statistically significant difference in the TUC levels between the groups.

The relationship between the AT and RC with TUC is shown in Table 2. The relationship between TUC and AT determined in the VO_{2max} test and RC was not significant ($p>.05$).

Table 1. Descriptive analysis of data of the groups (n=87)

Descriptive analysis of data	G1 (n=24) Mean ± SD	G2 (n=24) Mean ± SD	G3 (n=22) Mean ± SD	G4 (n=17) Mean ± SD	p	F	Binary comparisons
Age (years)	24.0 ± 1.6	24.1 ± 1.2	24.1 ± 1.3	24.3 ± 1.7	0.79	0.34	
Height (cm)	176.3 ± 5.1	176.1 ± 5.8	178.5 ± 4.2	177.0 ± 5.3	0.40	0.10	
Weight (kg)	73.8 ± 7.9	75.9 ± 8.6	78.6 ± 7.6	78.0 ± 7.7	0.20	1.57	
BMI ($kg.m^{-2}$)	23.8 ± 2.5	24.5 ± 2.3	24.6 ± 1.8	24.9 ± 2.0	0.41	0.98	
Body fat (%)	16.6 ± 4.3	18.8 ± 4.3	18.4 ± 4.1	21.8 ± 3.7	0.003**	5.02	1-4
TUC (sec)	195.9 ± 39.3	202.0 ± 47.9	193.6 ± 38.0	191.5 ± 42.3	0.86	0.25	
VO_2max ($ml.kg^{-1}.min^{-1}$)	49.4 ± 2.6	43.5 ± 1.4	40.0 ± 1.1	34.2 ± 1.8	0.31	1.23	
AT (sec)	428.6 ± 55.3	413.4 ± 105.5	371.2 ± 103.9	358.7 ± 119.6	0.07	2.68	
RC (sec)	595.6 ± 35.4	574.6 ± 43.6	547.1 ± 40.1	530.8 ± 59.6	0.000***	240.4	1-2; 1-3; 1-4; 2-3; 2-4; 3-4

Note. Values are mean ± SD; a Significantly different with pre-test at p<.001.
BMI: body mass index; TUC = time of useful consciousness, AT = anaerobic threshold, RC = respiratory compensation.



Note. TUC = time of useful consciousness, AT = anaerobic threshold, RC = respiratory compensation.

Figure 2. A-D. AT, RC times, TUC, and VO_{2max} levels of the groups by performance.

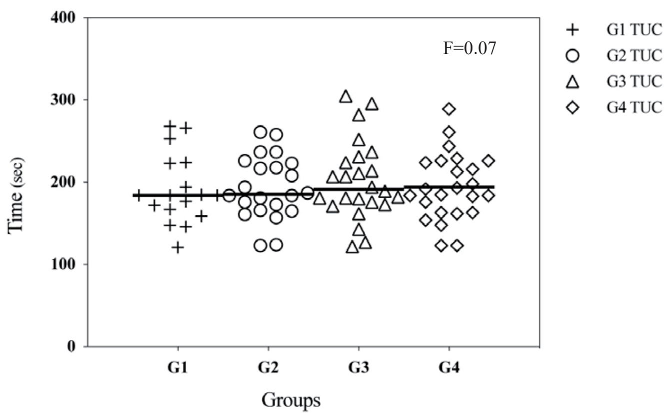
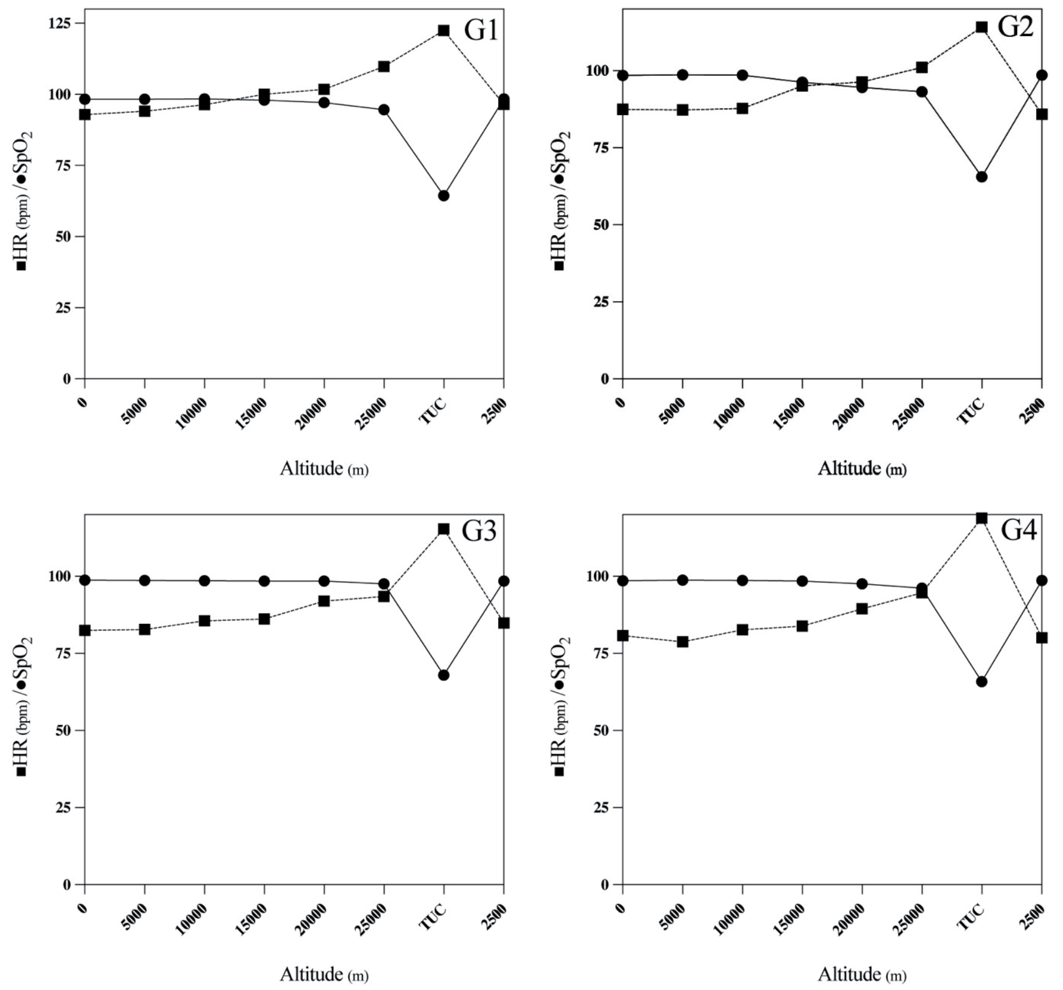


Figure 3. Comparison of TUC level of the groups separated by aerobic performance.

Table 2. The relationship of the participants' anaerobic threshold and respiratory threshold values with TUC

Pearson's R		**AT (sec)**	**RC (sec)**	**VO_{2max} ($ml.kg^{-1}.min^{-1}$)**	**Age (years)**	**Body fat (%)**	**BMI ($kg.m^{-2}$)**
Groups	TUC (sec)	0.19	0.08	0.07	-0.05	0.01	-0.06
	p	0.27	0.65	0.51	0.66	0.94	0.59
G1	TUC (sec)	-0.14	0.33	0.17	-0.16	0.11	-0.20
	p	0.83	0.59	0.45	0.64	0.64	0.38
G2	TUC (sec)	0.34	-0.02	-0.17	-0.18	-0.03	0.09
	p	0.42	0.96	0.42	0.41	0.89	0.68
G3	TUC (sec)	0.27	0.28	-0.44	0.14	0.13	0.13
	p	0.37	0.36	0.04*	0.53	0.55	0.55
G4	TUC (sec)	0.65	0.64	0.67	0.07	-0.13	-0.31
	p	0.08	0.09	0.003**	0.79	0.62	0.22

Note. TUC = time of useful consciousness, AT = anaerobic threshold, RC = respiratory compensation, BMI = body mass index.

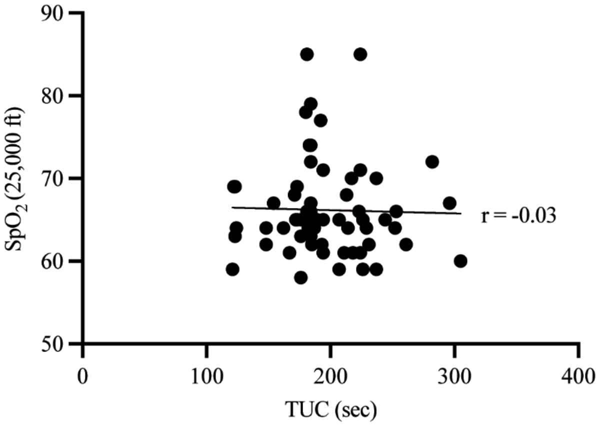


Note. HR= heart rate, SpO_2= peripheral oxygen saturation.

Figure 4. Comparison of SpO_2 and HR at the TUC level of the groups separated by aerobic performance.

As seen in Figure 4, there was no statistically significant difference between the groups' TUC level, SpO_2, and HR levels (p>.05).

It is shown in Figure 5 that the relationship between TUC and SPO_2 was not significant (r= -0.02) (p>.05).



Note. TUC = time of useful consciousness, SPO_2= peripheral oxygen saturation

Figure 5. Comparison of SpO_2 and TUC level.

Discussion and conclusions

The higher the altitude, the higher the risk of hypoxia exposure. Good fitness status or AC of the military or civil aviation sector persons and those interested in high-altitude sports have been thought of great importance to encounter hypoxic risk. In recent years, studies examining the relationships between AC and cognitive performance have been increasing. Aerobic activity is a powerful stimulant for the development of mental health and cerebral structural changes (Ankaralı & Bayramlar, 2019; Hendrikse, et al., 2022; Klil-Drori, Cinalioglu, & Rej, 2022). While an increase in hippocampal neuron number and cerebral blood volume (CBV) was observed in these studies with aerobic activity, increases in hippocampus volume and CBV were reported in human studies. Therefore, it can be expected that the cognitive performance of people with high AC who exercise will be better (Thomas, Dennis, Bandettini, & Johansen-Berg, 2012). It is unclear whether a difference in VO2max capacity would result in a differential time of useful consciousness tolerance in hypoxia responses. The present study aimed to determine the relationship between AC, anaerobic threshold, respiratory threshold, and time of useful consciousness of people working in the military or civil aviation sector and those interested in high-altitude sports.

Hypoxia is a serious aviation problem and may be a source of dangerous aerospace accidents (Kim, Ahn, Lee, & Kim, 2001). At altitude, the reduction in barometric pressure decreases arterial oxygen saturation (arterial SO_2) and arterial oxygen content (CaO_2) (Fulco, Rock, & Cymerman, 1998). Even for pilots in a pressurized cabin, hypoxia poses a risk at altitude. At night, at an altitude of 4940 feet, the effects begin to appear with reduced vision, and impaired cognitive ability becomes more pronounced as altitude increases. This significantly affects flight performance and safety (Rainford & Gradwell, 2006). As oxygen in the blood decreases, hypoxic effects begin, and when it starts to drop below 70% SpO_2, serious problems may begin. Hypoxia tolerance has been evaluated by the TUC, subjective symptoms, hypoxic ventilatory responses (HVR), and cardiovascular changes. It is not clear which physiological factors relate to the former parameters (Kim, et al., 2001). In the present study, it was assumed that there would be a significant difference between the TUC times of groups formed with participants with different aerobic capacities. However, the most striking result of this research is that the AC of the groups, which is accepted as the determinant of oxygen utilization capacity, did not make a significant difference in terms of TUC at 25000 feet. Also, the relationship between AT, RC, and TUC of groups was not significant. AT and RC values were better in groups with better aerobic performance, but this did not make a significant difference in TUC duration. Reference studies that can enrich our discussion are very limited. Previous studies evaluated the effect of training in hypoxic conditions on aerobic performance. While some studies have reported a positive effect (Czuba, et al., 2011; Mayo, Miles, Sims, & Driller, 2018; Ramos-Campo, et al., 2018), it has been shown to have no significant effect in some studies (Dufour, et al., 2006; Prommer, et al., 2007; Tadibi, Dehnert, Menold, & Bärtsch, 2007). An increase in oxygen-carrying capacity can be seen in those who perform endurance training in a hypoxic environment. Participants with higher VO_{2max} values did not train in any way in a normobaric or hypoxic environment. From this point of view, there may be differences between VO_{2max} developed in a hypoxic environment and VO_{2max} developed in physical activities at sea level (Ramos-Campo, et al., 2018). It has been shown in the study that exercise-induced movement and subsequent adaptation in hypoxia is less effective than expected in developing VO_{2max} in people living at high altitudes, and sometimes even lower when compared to those living at sea level. However, it has been stated that these individuals are more resistant to the effects of hypoxia on VO_{2max} (McClelland & Scott, 2019). Therefore, TUC is measured by testing pilots' hypoxic response in a simulated hypobaric chamber at an altitude of 25000 ft. The average TUC at this altitude is 3-5 minutes (Self, Mandella, White, & Burian, 2011; Shaver, 2009; Yoneda, Tomoda, Tokumaru, Sato, & Watanabe, 2000). According to Sucipta et al. (2018), military pilots stated that those with a lower TUC had higher fitness levels. In our study, AC, which is one of the determinants of fitness level, did not make a significant difference in terms of TUC. This was under the theory that people with high levels of physical fitness tend to have high oxygen consumption and so would be susceptible to hypoxia. The result was also consistent with that obtained in the study by Sucipta et. al (2018) where there was no relationship between the level of physical fitness and TUC in air force patients. The measurement procedure may also had effect on the absence of a relationship between physical fitness level and TUC in the current study. The difference in previous studies was obtained after the direct measurement using the treadmill with the gas analyzer, which is accepted as the golden criterion in the measurement of VO2max, the result of the direct measurement used for TUC reveals the relationship with each other. There are limitations in our research. Because the overall sample of participants were men, only men were included in the study and there were no experimental-control groups. Data on smoking were not collected. VO_{2max} test was not performed in the hypobaric chamber because there may be a risk of decompression due to the high altitude. For future studies, the relationship between anaerobic capacity and hypoxia or studies in which different physical and physiological characteristics are evaluated together in the same participants may contribute to the body of knowledge.

In conclusion, the results clearly show that there is no significant relationship between VO_{2max} determined on the treadmill with a gas analyzer and TUC determined in the hypobaric chamber at 25000 feet. For this reason, it is wondered whether high VO_{2max} plays a role in delaying hypoxia, and more importantly, it has been questioned whether it can be used in the personnel selection stages for the job. However, there is no significant relationship between VO_{2max} and TUC. Therefore, these data do not provide a valid criterion for personnel selection.

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STRATEGIES FOR A SELF-SELECTED UNANTICIPATED CHANGE OF DIRECTION MANEUVER AND THE RISK FOR ACL INJURY: FINDINGS FROM HAIE STUDY

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Abstract:

The purpose of the study was twofold: 1) to qualitatively investigate the different change of direction (COD) strategies used by females in an ecological situation; and 2) to evaluate the knee internal adduction moment and knee flexion during the first 30% of support as risk factors for anterior cruciate ligament (ACL) injury during these strategies. Ninety-four females, classified in ACTIVE and NON-ACTIVE groups performed five trials of a COD maneuver that were subsequently qualitatively evaluated. Kinematic and ground reaction force data were analyzed in the first 30% of support. To assess differences between strategies, we used a two-way repeated measures analysis of variance. Four strategies of 45° COD maneuvers were found. The different strategies involved either a cross-over with the right or left leg or had no cross-over. The statistical analysis revealed significant differences with a lesser knee internal adduction moment ($p<.05$) and a greater knee flexion angle during the strategies with a cross-over of the right foot compared to the other strategies ($p<.05$). Therefore, it is important to consider the potential effect of different strategies on ACL injury risk factors, as ACL injury risk factors may vary depending on the specific directional technique used.

Keywords: *knee moment, knee flexion, change of direction, COD strategies, anterior cruciate ligament*

Introduction

A sudden change of direction (COD) or cutting maneuver is often associated with non-contact anterior cruciate ligament (ACL) injuries in females (Pollard, Sigward, & Powers, 2007). The number of females participating in sport and exercise is increasing (Elliott-Sale, et al., 2021); thus, the higher number of active females is associated with potentially increased number of the ACL injuries. In addition, an ACL injury may lead to osteoarthritis later in life (Quatman & Hewett, 2009). To focus on preventing ACL injuries in females in high-risk sports, it is necessary to understand many strategies that could be used in performing the COD maneuver and to determine if these strategies are potentially risky.

The findings of studies in the literature have focused on biomechanical risk factors in relation to ACL injury during COD maneuvers focusing particularly on the knee adduction moment, knee flexion, menstrual cycle, laxity, and muscle activation (Fedie, Carlstedt, Willson, & Kernozek, 2010; Hanson, Padua, Blackburn, Prentice, & Hirt, 2008; Pollard, Braun, & Hamill, 2006; Wojtys, Huston, Boynton, Spindler, & Lindenfeld, 2002). Many of these studies constrain the strategy to be used and precise instructions are given to the participants to accomplish COD. However, there are many strategies that could be employed to accomplish a COD task. For example, Besier, Lloyd, Cochrane, and Ackland (2001) investigated several different methods of accomplishing COD maneuvers and found differences in several risk factors for ACL injury. However, the participants in this study were instructed on the methods to accomplish the COD maneuvers. A more ecological approach by letting the participants choose how to accomplish a COD task may be more informative as it relates to the risk of injury. It is certainly possible that the risk factors for ACL injury might be significantly affected by these different strategies used to perform the COD maneuver. However, there are few controlled studies that are ecological in nature allowing the participants to perform the task however they want.

Dempsey et al. (2007) and Dempsey, Lloyd, Elliott, Steele, and Munro (2009) demonstrated that different imposed techniques of a COD maneuver with focus on foot placement (i.e., foot wide, foot contact closer to the body's midline) resulted in increased peak valgus moments during weight acceptance phase of support. Besier et al. (2001) reported that different COD maneuvers elicited a combined load of flexion, valgus and internal rotation, whereas a cross-over technique had combined levels of flexion, varus and external rotation. So far, the above-mentioned studies had only been applied to men and had limited sample size. Moreover, these studies did not allow natural strategies, that is, a strategy chosen by the performer, in the performance of a COD maneuver and did not compare the types of different strategies often used in sports.

ACL injury is common in females due to many anatomic, hormonal, and neuromuscular risk factors. It is well known that females are predisposed to have greater quadriceps activation and lower hamstring activation in comparison to men (Harput, Soylu, Ertan, Ergun, & Mattacola, 2013). Moreover, anterior knee laxity is different between genders with females having significantly higher anterior knee laxity compared to males (Pollard, et al., 2006). Higher knee laxity may lead to higher internal knee adduction moments during a COD maneuver (Park, Stefanyshyn, Loitz-Ramage, Hart, & Ronsky, 2009). However, if male-based research is to be applied to females, there is a risk that the true potential risk for ACL injury in females will not be found. Dempsey et al. (2007, 2009) suggested that the results from the studies focusing only on men should not be applied to females. Presently, there are no controlled studies which evaluate ACL risk factors during different preferred strategies of COD maneuvers. Thus, it is necessary to conduct a controlled study that compares and/or evaluates different strategies of COD maneuvers in relation to possible risk factors for ACL injury in females.

To better the understanding of potential risk factors for ACL injury in females, it is necessary to focus on the individual and especially on different strategies that may be employed to perform a COD maneuver. Therefore, the first purpose of this study was to determine different strategies of an unanticipated COD maneuver used by females. This was accomplished by qualitatively classifying the different strategies used. The second purpose of this study was to compare specific biomechanical risk factors for ACL injury, that is, knee flexion (KF) angle in early support and the internal knee adduction moment (KIAM) according to the different strategies of COD maneuvers used by females. We hypothesized that the risk factors for ACL injury, knee flexion angle and the knee adduction moment during the first 30% of support would be different among the different strategies and that there would be no differences between ACTIVE and NON-ACTIVE participants in the risk factors for ACL injury.

Methods

Participants

An *a priori* sample size estimation was calculated based on key dependent variables (i.e., knee flexion and knee internal adduction moment) (Dempsey, et al., 2009). A power analysis for ANOVA (based on a pilot study of four types of direction changes) with minimal statistical power of 85% (p=.05) indicated that a total of 88 participants should be sufficient to expose statistically significant differences between each type of direction changes. A total 105 females were initially selected for this study. To be included in the study, ACTIVE participants (n = 51; age 22.8 ± 3.5 years; height 166.9 ± 6.0 cm; mass 59.9 ± 10.2 kg) had to be between 18 to 30 years of age, had at least five acceptable COD trials and participated in a moderate-intensity physical or sports activity at least 150 min per week or 75 min in high-intensity physical activity (World Health Organization, 2003). A NON-ACTIVE group (n = 43; age 23.3 ± 2.0 years; height 168.6 ± 2.6 cm; mass 63.0 ± 14.9 kg) had the same inclusion criteria as the active group with the exception that they did not regularly participate in a sports activity but could accomplish the COD task. The exclusion criteria for all eliminated individuals were them being smokers, pregnant or had a recent surgery, pain or illness. Eleven females were excluded from the study on the basis of incomplete data for the analysis of five trials of their COD maneuver. All participants signed an informed consent form that was approved by the Ethics and Research Committee of the University of Ostrava.

Experimental set-up

For kinetic and kinematic motion recording of COD maneuvers, we used a 10-camera high-speed motion analysis system (9x Oqus 700+ and 1x Oqus 510+, Qualisys, Inc., Gothenburg, Sweden) and large force plate (Kistler 9287CCAQ02, Kistler Instruments AG, Winterthur, Switzerland). A series of photocells (P-2RB/1, EGMedical, Ltd., Czech Republic) were aligned parallel to the approach runway to monitor the approach velocity prior the COD maneuver. A left path away from the force platform was outlined with the tape to define the direction at which the females had to accomplish a COD maneuver at an angle of 45°. The required unanticipated signal (i.e., left arrow or straight arrow) was displayed on the wall in front of a projector, which was used together with the timekeeper that triggered the signal at the end of the runway.

Protocol

After signing the informed consent, participants' height and body mass were measured prior to the initiation of data collection. Additionally, participants kicked a ball three times into a marked goal area to identify the dominant limb or the lower extremity that was used for most trials (Hoffman, Schrader, Applegate, & Koceja, 1998). Reflective markers were placed on thighs, shanks, feet and pelvis (McClay & Manal, 1999). All females were provided with neutral running shoes in which to perform the study. Before the COD maneuver, running and walking were used as a warm-up. Each participant completed a practice session which included several randomly cued trials of COD maneuvers on the dominant leg (the right limb for all participants). During the practice trials, the average approach running speed was measured and used as the target speed of analyzed trials. Following the practice trials, the first photocell was placed at a distance of 90% of the individual's stride length plus a distance for correction of the distance traveled in 0.2-s relative to participant's speed. In addition, the investigator triggered a random signal that was displayed in sufficient size at the end of the runway. Then several trials of the COD maneuvers were performed. The velocity was not standardized but did not fall below the values obtained from the practice session.

Participants were instructed to run and change direction as quickly as possible. Between each trial, approximately a one-minute interval was given to the participant in order to reduce the potential effect of fatigue. Individual trials continued until the five successful trials of the COD maneuver were completed. Trials were deemed successful if: 1) the right foot established contact with the force platform; 2) the following contact of the left foot was in the marked lane of a 45° angle; and 3) approach speed was not lower than in the practice trials.

The COD protocol was part of biomechanical protocol in a large study called 'Healthy Aging in Industrial Environment – Program 4 (4HAIE)' (Jandacka, et al., 2020). The main purpose of the larger study was to examine the impact of physical activity in a polluted environment. Data were collected from the participants during a two-day laboratory testing protocol. A part of the two-day testing protocol included biomechanical testing of running, walking and COD maneuvering. The full description of the experimental procedures and the kinematic and kinetic modelling approaches have been described previously (Jandacka, et al., 2020).

Data analysis

Five trials of COD maneuver for each female were qualitatively evaluated by two independent reviewers. To classify the COD strategies, the assessors evaluated three steps during COD: 1) the left foot in front of the force platform before the right foot contact with the force platform; 2) the right foot on the force platform; and 3) the subsequent step of the left foot outside of the force platform. The foot position was assessed from the coronal plane midline of the pelvis. After comparing the results of the qualitative evaluation of each trial, probable discrepancies were then discussed and evaluated by the two reviewers.

The maximum right knee adduction moment (KIAM) and the maximum right knee flexion angle (KF) were analyzed during the first 30% of support phase. Donnelly, Chinnasee, Weir, Sasimontonkul, and Alderson (2017) suggested that this was the period of support when the knee was most at risk for an ACL injury. The peak values of KIAM were normalized to body mass for the COD maneuvers.

Statistical analysis

For the second aim of this study, the distribution and the normality of dependent variables (i.e., right KIAM and right KF) were determined via a univariate analysis using strategy as an independent measure and by the Shapiro-Wilks test (α=.05). Depending on the distribution normality of the data, the differences between the types of direction changes for the mean of the five trials of each participant were assessed using two-way repeated measures analysis of variance (activity status X COD strategy X participants). If the data for the dependent measures were not normally distributed, a Kruskal-Wallis non-parametric test was used. The ANOVA was performed separately for both the KIAM and KF parameters. The criterion alpha level was set at 0.05. A Bonferroni correction was used for *post-hoc* tests when necessary.

Results

We identified four strategies of direction changes during the unanticipated COD maneuvers in which the right foot contacted the force platform (see Figure 1, Table 1). The COD strategies included two with a cross-over pattern (Strategies 2 and 4) and two without it (Strategies 1 and 3). The dependent measure KIAM was found to be non-normally distributed, while KF was normally distributed.

In the statistical analysis for KIAM, there was no statistically significant activity status X change in direction strategy interaction (p=.84, partial eta^2 = 0.002) nor was there a significant difference between the ACTIVE and NON-ACTIVE participants (p=.38, partial eta^2 = 0.002). The statistical analysis did reveal a statistically significant difference for KIAM across strategies (p=.001, partial eta^2 = 0.058). The *post-hoc* analysis revealed the main difference was between the types of direction

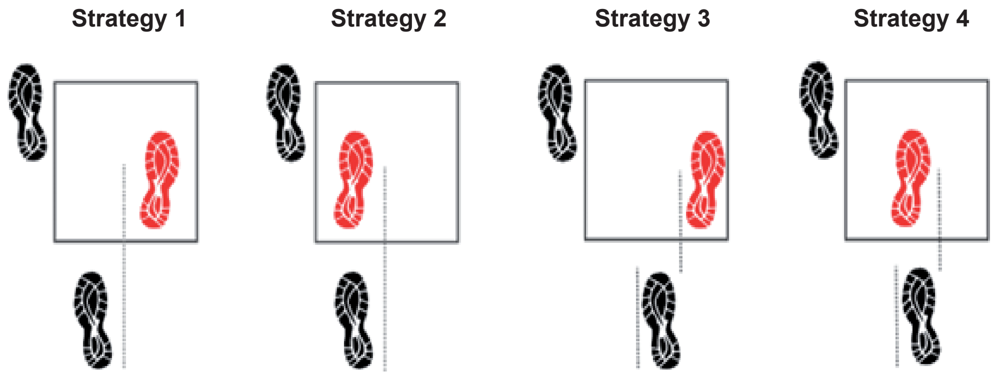

Figure 1. The types of strategies used by participants when given no instructions on how to accomplish a change of direction maneuver (left foot – black; right foot – red): 1) left foot without cross-over and the right foot without cross-over; 2) left foot without cross-over and right foot with cross-over; 3) left foot with cross-over and right foot without cross-over; and 4) left foot with cross-over and right foot with cross-over. Strategies 2 and 4 were considered cross-over strategies, while 1 and 3 were not. The contact of the foot on the force platform is illustrated. The square represents the force platform.

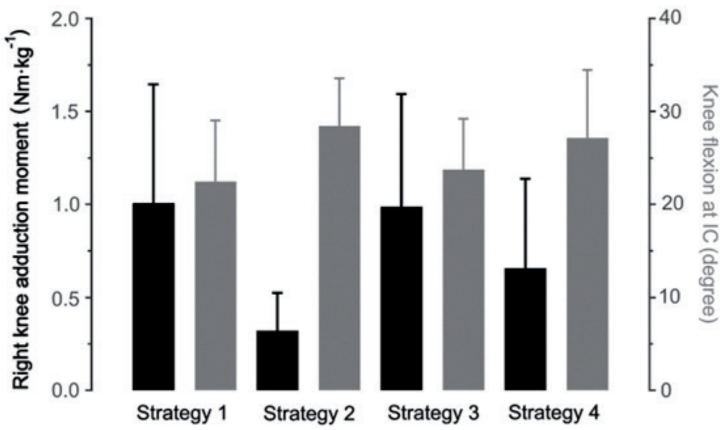

Figure 2. The graph illustrates the average peak magnitude of the right knee internal adduction moment normalized to body mass (black) and right knee flexion angle during the first 30 % of support phase (grey) across different types of direction changes during an unanticipated change of direction maneuver.

Table 1. Descriptive mean values (±standard deviation) of the variables during the change of direction maneuver for the different strategies

	Strategy 1		Strategy 2		Strategy 3		Strategy 4	
Variable	ACTIVE	NON-ACTIVE	ACTIVE	NON-ACTIVE	ACTIVE	NON-ACTIVE	ACTIVE	NON-ACTIVE
Frequency of occurrence	149	91	2	11	65	56	39	57
Knee adduction moment	1.03±0.69[a]	0.97±0.54[d,f]	0.49±0.18	0.29±0.20[c,d]	1.05±0.68[b]	0.91±0.50[c,e]	0.66±0.46[a,b]	0.65±0.50[e,f]
Knee flexion	22.37±6.97	22.60±5.91	32.09±0.24	22.77±5.34	24.24±5.77	23.14±5.14	28.62±9.01	26.14±5.80
Approach velocity	4.28±0.52[g]	3.96±0.48[i,j]	3.56±0.65	3.71±0.47[j]	4.06±0.46[k]	4.06±0.46[k]	4.20±0.44[g,h]	3.94±0.42[i,k]

Note. Means with the same superscript are statistically different in pairwise comparison analysis between strategies ($p<.05$). Knee adduction moment ($Nm \cdot kg^{-1}$); velocity ($m \cdot s^{-1}$); knee flexion (degrees).

changes without cross-over of the right foot (Type 1 and Type 3) with types of direction changes when the right foot did a cross-over (Type 2 and Type 4) ($p=.001$, partial eta^2 =.002).

For the KF parameter, again there was no statistically significant activity status X COD strategy interaction ($p=.308$, partial eta^2 = 0.008) nor was there a significant difference between the ACTIVE and NON-ACTIVE groups ($p=.151$, partial eta^2 = 0.004). However, there was a significant difference between the COD strategies ($p=.001$, partial eta^2 = 0.087). The *post-hoc* analysis revealed that KF was largest with the cross-over of the right foot (Type 2) indicating that the knee was in a more flexed or less extended position. However, when the right foot did not cross-over (Type 1 and Type 3), the KF angle was less (i.e., more extended) than in the strategies with the cross-over of the right foot (Type 2 and Type 4) (p=.001, partial eta^2 = 0.077).

Discussion and conclusions

The first purpose of this study was to identify different types of direction changes during an unanticipated COD maneuver. When we visually inspected the data, we found that there were four main types of strategies commonly used by the participants (see Figure 1), two strategies that employed a cross-over technique and two that did not. The second purpose of this study was to compare the maximum of the knee internal adduction moment and knee flexion angle at the initial foot contact according to the different strategies of the COD maneuvers used by the participants and between the ACTIVE and NON-ACTIVE groups. We hypothesized that there would be difference in the knee internal adduction moment or the knee flexion angle at initial contact between the COD strategies but not between the groups. The main finding of the present study suggests that the types of direction changes with a cross-over of the right foot (Strategies 2 and 4) showed significantly lower knee internal adduction moments and higher knee flexion angles at the initial contact than the types without cross-over of the right foot (Strategies 1 and 3) and that activity status did not affect the COD strategy results.

The results of the current study for the knee adduction moment and knee flexion angle at the initial contact were similar to those in studies that used an unanticipated COD maneuver (Beaulieu, Lamontagne, & Xu, 2009; Kim, et al., 2014). Unlike other quasi-experimental studies, these results were achieved using an ecological design allowing the performance of a self-selected COD maneuver by participants (i.e., females) who generally are at a greater risk of ACL injury compared to men (Dempsey, et al., 2007; Dos'Santos, Thomas, Comfort, & Jones, 2021; Hewett, et al., 2005). The values of KIAM during Type 1 (1.02 ± 0.61 Nm•kg^{-1}) and Type 3 (0.99 ± 0.59 Nm•kg^{-1}) in this study were comparable to the values of experienced athletes (0.9 ± 0.6 Nm•kg) (Sigward & Powers, 2006). For the KF angle during the first 30% of support, Vanrenterghem, Venables, Pataky, and Robinson (2012) reported an angle of 14.9 ± 4.1° of KF for the same COD angle running at a speed of 4.0 m•s^{-1} or approximately the speed used by the participants in our study. Similar results were reported by Beaulieu et al. (2009) where the KF angle was reported as 18.0 ± 6.8° at 4.0 to 5.0 m•s^{-1} in an unanticipated COD maneuver. These KF angles are less than the angles observed in the current study (angles ranging from 22.4 to 28.2°). However, the authors in the previous studies did not address the cross-over situations, which had the lowest KF angles in our study. It was also not clear whether the trials in Vanrenterghem et al. (2012) were unanticipated or anticipated, which certainly could affect the results of KF. Unlike the above-mentioned studies, higher knee flexion values (e.g., 29.3 ± 6.2°) were found at 90° COD (Sheu, Gray, Brown, & Smith, 2015). It appears that a higher angle of COD or cross-over may increase knee flexion (i.e., knee is more flexed) and thus possibly less risk for ACL injury. Regardless of crossing over or not or increasing the direction angle, all strategies found in this study exhibited a risk for ACL injury.

There are several strategies that can be used for performing a sudden unanticipated COD maneuver. These options were the possible strategies for the execution of a sudden change of direction used by females in the current study. Sigward and Powers (2006) reported that beginners and experienced female athletes employed different neuromuscular control strategies during a COD maneuver, thus, beginners may adopt a protective strategy during this maneuver. Dos'Santos et al. (2021) and Potter et al. (2014) analyzed a maneuver in which the left foot crossed over and found no differences between experienced and non-experienced participants. While not all participants in our study engaged regularly in sports activities that included a COD maneuver, we did not find that there were differences in the risk factors between ACTIVE and NON-ACTIVE participants.

KIAM was different with regard to the type of direction changes during the unanticipated COD maneuver. This study showed that types of direction changes with cross-over of the right foot decreased the knee internal adduction moment compared to the strategies that did not use a cross-over. Studies by Besier et al. (2001) and Kim et al. (2014) showed greater knee valgus moments during side-step techniques compared to cross-over techniques. Unlike those studies, our study was conducted with females who had a greater risk of ACL injury at higher speeds when injury is more likely (Vanrenterghem, et al., 2012; McLean, Myers, & Walters, 1998). Dos'Santos, McBurnie, Thomas, Comfort, and Jones (2019) reported that when the foot crossed the body midline, the ground reaction force vector was positioned medial to the knee thus generating a knee varus or adduction moment. In contrast, in a maneuver without a cross-over, the ground reaction force vector was positioned lateral to the knee creating a knee valgus or abduction moment. With respect to knee adduction moment, this technique (cross-over) appeared to be a safety strategy for ACL injury for an unplanned COD. This finding suggests that the cross-over strategy may be important to include in training. Relative to ACL injuries, the COD without a cross-over appears to be a higher risk compared to the cross-over technique.

As KF increases, that is the knee becomes less extended, this occurs with the strategies that included a cross-over. KF angles ranged from 22.37°, 28.16°, 23.77°, 26.69° for strategy 1 to strategy 4 (see Table 1). Zahradnik, Jandacka, Farana, Uchytil, and Hamill (2017) suggested that a KF angle less than 30° (i.e., with a straighter, more extended leg) placed the athlete in a precarious position for an ACL injury. It certainly appears that the strategies categorized in this study may place the participant in a position that could lead to an ACL injury. The results of the current study support the notion that, with a cross-over strategy, ACL risk may be reduced by an increased knee flexion angle (Benjaminse, Otten, Gokeler, Diercks, & Lemmink, 2017). Studies by McGovern et al. (2015) and Schreurs, Benjaminse, and Lemmink (2017) confirmed that females displayed less KF than males during a typical COD maneuver. Additionally, a higher KF angle was found during cross-over cuts compared to side-step cuts (McGovern, et al., 2015; Potter, et al., 2014). These findings are similar to those in our study. We can speculate that the differences in KF values (a less extended knee) between Type 2 and Type 4 compared to Beaulieu et al. (2009) and Vanrenterghem et al. (2012) may be higher due to a crossover strategy.

There are some limitations of our study that should be acknowledged. This study only considered a 45° moment maneuver in which we gave no instructions to the participant in how to perform the movement. The left foot was not analyzed with regard to the ground reaction force. Specifically, in strategy 2, the left foot may have been more loaded in terms of the reaction forces with respect to the ACL. Additionally, we evaluated only two risk factors considered to be the most prevalent (internal knee adduction moment and knee flexion angle during the first 30% of support) as indicators of ACL injury risk. While these are two of the more prevalent risk factors for ACL injury, there are others that we did not assess (e.g., the internal and external rotation of foot relative to the knee, which is the next most prevalent cause of ACL injury) (Schreurs, et al., 2017). Lastly, we did not directly measure running speed. It has been suggested that the appropriate speed for evaluating knee loading mechanisms in females in a 45° side COD maneuver should be approximately 4 $m \cdot s^{-1}$ (Vanrenterghem, et al., 2012). The approach velocities in our study were 4.14 ± 0.53 $m \cdot s^{-1}$, 3.60 ± 0.43 $m \cdot s^{-1}$, 4.11 ± 0.51 $m \cdot s^{-1}$, and 4.00 ± 0.41 $m \cdot s^{-1}$ for Type 1, Type 2, Type 3, and Type 4, respectively. With the exception of strategy type 2, all velocities were in the suggested range.

To conclude, our results suggest that females may use at least four different methods to accomplish an unanticipated COD task. We also found that two of the main risk factors for ACL injury (e.g., knee adduction moment and knee flexion angle at the initial contact) may be different with regard to the four strategies of the COD maneuver performed. The KF angle increased with the presence of a cross-over in COD while the knee adduction moment decreased with the presence of the cross-over strategy. In both cases, the risk of an ACL injury was decreased in the strategies with a cross-over. Change of direction maneuvers without a cross-over of the right foot may be associated with an increased biomechanical loading (e.g., higher knee adduction moments) of the ACL compared to other strategies for accomplishing COD tasks in females possibly placing these females at risk for ACL injury. These results also suggest that it may not be possible to compare knee kinematics/kinetics from one study to the next unless that type of strategy in each study is the same. In future studies, it may be prudent to define the COD task explicitly or explain directly which type of change of direction strategy was used.

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GUIDELINES FOR CONTRIBUTORS

FOCUS AND SCOPE

Kinesiology – International Journal of Fundamental and Applied Kinesiology (print ISSN 1331- 1441, online ISSN 1848-638X) publishes twice a year scientific papers and other written material from kinesiology (a scientific discipline which investigates the art and science of human movement; in the meaning and scope close to the idiom "sport sciences") and other adjacent human sciences focused on sport and exercise, primarily from anthropology (biological and cultural alike), medicine, sociology, psychology, natural sciences and mathematics applied to sport in its broadest sense, history, and others. Contributions of high scientific interest, including also results of theoretical analyses and their practical application in physical education, sport, physical recreation and kinesitherapy, are accepted for publication. The following sections define the scope of the journal: Sport and sports activities, Physical education, Recreation/leisure, Kinesiological anthropology, Training methods, Biology of sport and exercise, Sports medicine and physiology of sport, Biomechanics, History of sport and Book reviews with news.

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Journals

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Kasović, M., Medved, V., & Vučetić, V. (2002). Testing of take-off capacities in the lower extremities of top football players. In D. Milanović & F. Prot (Eds.), *Proceedings Book of 3rd International Scientific Conference "Kinesiology – New Perspectives"* (pp. 677–680). Zagreb: Faculty of Kinesiology, University of Zagreb.

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