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Differences in the psychophysiological response between normal weight and overweight young recreational athletes in strength training

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ABSTRACT

Background: Strength training is widely recognized for its benefits in young recreational athletes, yet limited research has explored its effects on heart rate variability (HRV) across different body compositions. This study aimed to analyse the autonomic modulation differences between normal-weight and overweight recreational athletes during strength training. **Methods:** A total of 63 male recreational athletes (23.8 ± 3.6 years, 174.9 ± 8.2 cm, 70.8 ± 11.7 kg) were categorized into normal-weight (Body Mass Index < 25) ($N = 38$) and overweight (Body Mass Index > 25) ($N = 25$) groups. Participants performed three sets of 10 repetitions at 70% 1RM for both squats and bench press. HRV parameters, including RMSSD, SDNN, and PNN50, were measured before, during, and after training. Additionally, heart rate (HR), rate of perceived exertion (RPE), and strength levels were assessed. **Results:** HR significantly increased during training in both groups, with a greater post-exercise HR elevation observed in the normal-weight group. HRV parameters (RMSSD, SDNN, PNN50) decreased significantly during training in the normal-weight group, indicating greater autonomic stress. RPE increased post-exercise in both groups, while the overweight group demonstrated higher baseline strength levels. **Conclusion:** Strength training induced acute autonomic stress in both groups, with greater HRV suppression observed in normal-weight athletes, suggesting a higher physiological demand. In contrast, overweight athletes displayed better baseline strength levels and potentially greater adaptability to strength training. These findings highlight the need for individualized training prescriptions based on body composition to optimize performance and recovery in recreational athletes.

Keywords: HRV, Strength, Recreational athletes, Physiological response, BMI.

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INTRODUCTION

Recently there has been an increase in the number of young athletes who focus on strength training, as well as an increase in training focused on improving heart rate variability (Nuzzo, 2020; Thompson, 2022). The benefits of strength training are notable in the young athlete population. Strength training not only improves muscle strength, but it also contributes to bone health, body composition, and enhances injury prevention (Faigenbaum et al., 2013). Strength training has shown to be beneficial to the mental health of young athletes, increasing self-confidence, self-esteem and body image, and reducing levels of anxiety and depression (Robinson et al., 2023). Also, it's been shown an improvement in functional capacity and even help prevent the development of chronic metabolic diseases like type II diabetes and obesity (Granacher et al., 2016). Not only does it help with metabolism and function, but it's also been linked to changes in the autonomic nervous system and Heart Rate Variability (HRV).

The stress of the autonomous nervous system can be measured by HRV, which is a non-invasive method to assess the prevalence of the sympathetic or parasympathetic branches to better adapt to different trainings (Selig et al., 2004). Also, strength training has proven to be an interesting method for modulating heart rate variability and thus avoiding potential risks to overall cardiovascular health (Güngör et al., 2024).

Historically, aerobic training is the most studied in the acute response for HRV values, however, the findings on modulation of vagal tone through strength training do not reflect positive results (Cooke & Carter, 2005). These effects depend on several factors, such as training intensity, exercise selection, cognitive workload and the individual's previous experience in physical activities (Díaz-García et al., 2023; Heffernan et al., 2007). Interest in studying the relationship between strength training and HRV is also due to growing evidence that reduced HRV is associated with an increased risk of cardiovascular accidents and mortality, especially in individuals with chronic diseases such as hypertension or heart failure (Buchheit & Gindre, 2006), and in overweight or obese individuals (Reena Tiwari et al., 2021). Identifying effective interventions to improve or maintain healthy HRV is crucial for the prevention and management of these conditions.

Recent studies have observed that strength training programs performed at moderate to high intensity can increase HRV, suggesting an improvement in the balance between sympathetic and parasympathetic activity (Lee et al., 2024). Strength training in overweight individuals (BMI > 25) is related to HRV through the relationship of several mechanisms. One is the reduction of systemic inflammation and oxidative stress, which are common in overweight individuals and may contribute to autonomic dysfunction (Esco et al., 2010). In addition, strength training improves insulin sensitivity and endothelial function, factors that influence autonomic modulation and HRV (Ashor et al., 2015).

Studies evaluating strength training traditionally use methods such as 1RM (one maximum repetition) to establish loads, but some authors suggest the possibility of monitoring strength training loads through pulsometers and heart rate variability (Buchheit, 2014; Stanley et al., 2013).

Assessing the acute responses of the autonomic nervous system during strength training provide interesting results that would help to discover whether strength training can generate adaptations of the cardiac system. This study aimed to analyse differences in autonomic modulation between normal weight and overweight young recreational athletes during a strength training. We hypothesized that both groups would decrease their HRV values due to the stress of the strength training, and that heart rate variability would be lower in the overweight group.

METHODS

Participants

We analysed N = 63 male recreational athletes (23.8 ± 3.6 years. 174.9 ± 8.2 cm. 70.8 ± 11.7 kg), which were divided in two groups: normal weight group (BMI < 25, N = 38) and overweight group (BMI > 25, N = 25). Subjects were stratified according to their Body Mass Index (BMI), determined by calculating BMI as weight in kilograms divided by the square of height in meters (kg/m^2), using anthropometric data obtained during the baseline assessment. This study is quasi-experimental research. Convenience sampling was used, as participants were recruited among volunteers that agreed to participate in the study. The experimental procedures were explained to all the participants, following the Declaration of Helsinki, and approved by the Ethics Committee of the University (CIP/18/74).

Procedure

All the participants performed a strength training following the procedures of previous research (Bustamante-Sánchez et al., 2018; Bustamante-Sánchez & Clemente-Suárez, 2020). 1 RM (maximum repetition) tests were conducted between 09:00 a.m. to 12:00 p.m., under the same environmental conditions (temperature 25–26°C, humidity 52–54%). Participants were asked to conduct the training session with at least 8 h of sleep, hydrated (drink at least 500 ml of liquid between wake up and the test), and having a standardized breakfast composed of fruit juice, milk, and cereals. The participants verbally agreed to have followed these rules prior to the strength intervention.

The estimation of 70% of 1 RM was calculated on a separate day, prior to baseline testing, for all two exercises.

A 15min rest was allowed before every 1 RM assessment. Training session started with a standardized warm up for 15 min. Before and after warming up participants conducted the flicker fusion test.

After warming up, participants performed 3 sets composed of the following exercises:

- 10 repetitions of squat at 70% of the 1 RM.
- 10 repetitions of bench-press at 70% 1 RM.

Before and after the 1 RM assessment, the following parameters were analysed:

- (1) Body mass (to the nearest 0.1 kg) was measured by a bio impedance analyser (InBody 720, Biospace Co. Ltd., Seoul, South Korea).
- (2) Body height (to the nearest 1 cm) was measured by a portable stadiometer (SECA, Leicester, UK).
- (3) Cortical arousal through the Critical Flicker Fusion Threshold (CFFT) in a viewing chamber (Lafayette Instrument Flicker Fusion Control Unit Model 12,021) following the procedures conducted in previous studies (Bustamante-Sánchez & Clemente-Suárez, 2020).
- (4) Isometric handgrip strength by a grip dynamometer (Takei Kiki Koyo. Japan). (Bustamante-Sánchez & Clemente-Suárez, 2020).
- (5) Horizontal jump with hands on waist.
- (6) Jump tests (Squat Jump, Countermovement Jump, and Abalakov jump) were assessed through the Optojump system (Microgate Engineering, Bolzano, Italy).
- (7) Subjective perceived stress was assessed with a 0-100 scale, like in previous studies (Bustamante-Sánchez et al., 2018; Bustamante-Sánchez & Clemente-Suárez, 2020).

- (8) Rate of perceived exertion (RPE) in a 6-20 rank was assessed through the Borg scale (Borg, 1982).
- (9) Heart Rate Variability (HRV) through a Polar v800 heart rate monitor (Polar Electro Oy, Finland) validated to record RR function to analyse heart rate variability (HRV) (Giles, Draper & Neil, 2015), by the Kubie's HRV software (University of Kuopio, Kuopio, Finland) following procedures of previous research (Bustamante-Sánchez et al., 2021).

The data obtained was divided into three segments, which are used to summarize the entire procedure. The first segment was designated the 'pre-test' and consisted of measurement in basal state without intervention. The second segment was designated 'during the strength tests' and consisted of measurements during strength tests. The third segment was designated the 'post-test' and consisted of measurement after 5 minutes of rest, during which an attempt was made to return to the basal state.

Statistical analysis

The IBM SPSS statistical package (version 26.0; SPSS, Inc. Chicago, Illinois) was used to analyse the data. Normality assumptions were checked with a Kolmogorov-Smirnov test. Descriptive statistics were presented as mean and standard deviation. A mixed ANOVA test, with three repeated measures for HRV tests and two repeated measures for the arousal and physical tests was used. Moreover, one factor (BMI group) was added to compare the effect of the test, the effect of the BMI group, and the interaction among the type of test, and the effect of the BMI group. To analyse pairwise comparisons, a Bonferroni post hoc test was used. The level of significance for all the comparisons was set at $p < .05$. For the HRV analysis we used the average of the intervals.

RESULTS

Table 1 shows the heart rate variability differences among BMI groups and pre, during, and post measurements. Heart rate (HR) was higher during strength training (108.5 ± 22.6 ; 102.3 ± 20.8) than in the pre-measurements (91.3 ± 15.4 ; 90.1 ± 15.99) in both groups. HR was also higher in the normal weight group (BMI < 25) during the post-test (97.4 ± 17.8) than during the pre-measurement (90.1 ± 15.99). RMSSD, SDNN and PNN50 were lower during strength training than during the pre-test in the normal weight group (31.2 ± 15.8 ; 43.8 ± 19.5 ; 8.26 ± 5.90 vs 41.9 ± 22.3 ; 58.3 ± 32.5 ; 12.7 ± 13.7). SDNN was lower in the post-test than in the pre-measurement. HF was higher for the normal weight group when compared to the overweight group during the pre-test (23.4 ± 8.86 vs 15.6 ± 2.85).

Table 2 shows the arousal and physical differences among BMI groups and measurement instants. RPE was higher in the post measurements than in the pre-tests in both BMI groups ($p < .05$). Strength levels were higher in the overweight group than in the normal weight group during the pre-tests ($p < .05$).

DISCUSSION

This study aimed to analyse differences in autonomic modulation between normal weight and overweight recreational athletes during a strength training. The findings supported the initial hypothesis: both groups decreased their HRV values during the training showing greater stress. When comparing pre- and post-exercise results in groups with different BMI, the findings suggest that, although strength exercises improve physical performance, BMI may influence perceived exertion and jumping performance.

Table 1. Heart-rate variability results.

	Pre				During				Post				Strength and BMI effect		
	BMI > 25		BMI < 25		BMI > 25		BMI < 25		BMI > 25		BMI < 25		F	p-value	η^2
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD			
HR	91.3 [‡]	15.4	90.1 ^{‡, ###}	15.9	108.5 [‡]	22.6	102.3 [‡]	20.8	102.1	24.2	97.4 [‡]	17.8	0.296	.745	.008
RMSSD	41.9	22.3	50.6 [‡]	38.2	35.3	22.7	31.2 [‡]	15.8	44.3	28.8	36.3	21.6	1.027	.363	.028
SDNN	58.3	32.5	63.3 ^{‡, ###}	26.9	48.4	18.4	43.8 [‡]	19.5	58.4	28.2	48.8 [‡]	20.8	1.084	.344	.029
PNN50	12.7	13.7	17.4 [‡]	17.1	11.6	14.6	8.26 [‡]	5.90	13.1	13.6	12.8	16.9	1.102	.338	.030
SD1	31.4	14.2	48.1	57.9	26.1	16.1	25.8	17.0	32.8	19.3	26.7	15.1	0.871	.423	.024
SD2	86.4	40.6	79.7	33.6	67.3	39.3	58.7	27.9	80.1	35.3	66.6	26.0	0.119	.888	.003
SD1/SD2	0.39	0.08	0.97	2.13	0.37	0.09	0.87	2.53	0.44	0.14	0.95	1.84	0.003	.997	.000
LF (n.u.)	81.0	8.35	76.1	9.07	76.7	13.4	76.7	15.6	76.1	14.4	77.8	12.7	0.612	.545	.017
HF (n.u.)	15.6 [*]	2.85	23.4 [*]	8.86	21.0	11.3	20.7	9.45	21.8	14.2	20.2	12.4	2.261	.112	.061
LF/HF	5.30	1.06	4.50	4.70	4.90	3.28	0.49	2.67	5.81	5.82	5.40	3.15	0.061	.941	.002

Note. BMI: Body Mass Index. M: Mean. SD: Standard Deviation. t: t test. HR: Heart Rate. RR: R-R interval. RMSSD: Root mean square of successive RR interval differences. SDSD: Standard Deviation of the differences between successive NN intervals. SDNN: Standard deviation of NN intervals. PNN50: Percentage of successive RR intervals that differ by more than 50ms. SD1: Poincaré plot standard deviation perpendicular to the line of identity. SD2: Poincaré plot standard deviation along the line of identity. SD1/SD2: Ratio of SD1-to-SD2. LF: Low-frequency band (0.04–0.15 Hz). HF: High-frequency band (0.15–0.4 Hz). LF (n.u.): Relative power of the low-frequency band (0.04–0.15 Hz) in normal units. HF (n.u.): Relative power of the high-frequency band (0.15–0.4 Hz) in normal units. ‡ Difference with pretest ($p < .05$). †† Difference with Strength period ($p < .05$). ††† Difference with post-test ($p < .05$). *Differences between BMI groups ($p < .05$).

Table 2. Arousal and physical results.

	Pre				Post				Strength and BMI effect		
	BMI > 25		BMI < 25		BMI > 25		BMI < 25		F	p-value	η^2
	M	SD	M	SD	M	SD	M	SD			
Flicker (hz)	38.6	4.51	38.9	4.32	38.8	3.64	40.6	10.6	0.219	.642	.004
Stress (0-100 rank)	27.3	17.1	25.3	17.9	45.6	18.9	49.1	21.0	0.344	.560	.007
RPE (6-20 rank)	7.11 [‡]	1.45	7.18 [‡]	2.85	14.3 [‡]	3.00	13.4 [‡]	4.31	0.453	.504	.009
Strength (kg)	50.5 [*]	11.6	41.6 [*]	9.29	49.5	12.2	42.6	9.87	1.934	.171	.040
SJ (cm)	30.3	8.35	30.5	8.15	29.6	8.30	30.8	8.39	0.385	.538	.008
CMJ (cm)	33.5	8.18	33.6	7.93	32.5	7.86	34.2	7.73	1.263	.267	.027
ABK (cm)	38.1	8.76	38.9	10.9	35.5	8.05	39.9	10.7	3.434	.070	.071

Note. BMI: Body Mass Index. M: Mean. SD: Standard Deviation. RPE: Rate of Perceived Exertion. SJ: Squat Jump. CMJ: Countermovement Jump. ABK: Abalakov Jump. ‡ Difference with pre-test ($p < .05$). †† Difference with post-test ($p < .05$). * Differences between BMI groups ($p < .05$).

The results of this study revealed a significant reduction in heart rate variability (HRV) during strength training in both normal-weight and overweight athletes, highlighting an acute autonomic stress response. RMSSD, SDNN, and PNN50 values were notably lower during the training session compared to pre-exercise levels, with a more pronounced decrease observed in the normal-weight group. These findings align with previous studies indicating that strength training acutely suppresses parasympathetic activity while increasing sympathetic dominance, leading to decreased HRV (Kingsley & Figueroa, 2016). Although previous research has suggested that overweight individuals tend to have lower baseline HRV due to impaired autonomic function (Lopes et al., 2007), our results did not show a significantly different HRV response between groups. This may be attributed to the fact that the participants were recreational athletes who had undergone previous training adaptations that could mitigate potential baseline autonomic differences. Additionally, strength training has been reported to improve HRV over time, particularly in individuals with lower baseline values, through mechanisms such as enhanced endothelial function and reduced inflammation (Selig et al., 2004). Comparing our findings to prior studies, Figueiredo et al. (2015) (Figueiredo et al., 2015) found that HRV suppression during strength training is dependent on the training load, with higher intensities leading to more pronounced reductions. Similarly, Melo et al. (2008) (Melo et al., 2008) observed that eccentric strength training in healthy older adults led to HRV reductions, suggesting that training modality plays a role in autonomic responses. However, some studies have reported that strength training does not lead to significant HRV changes, particularly when performed at moderate intensities (Lemos et al., 2018). These discrepancies may stem from differences in participant demographics, training protocols, and HRV measurement methods.

It was also found that perceived stress levels increased in both groups after the strength exercise protocol. This is in line with the findings of other studies which indicate that high-intensity training, such as strength exercises, may induce a temporary increase in perceived stress due to the physical and psychological demand of the effort (Atakan et al., 2021). Both groups experienced an increase in perceived stress, and there were no significant differences between the two groups. Walker et al. (2020) (Walker et al., 2020) found similar results. They reported that strength exercise increases cortisol levels and perceived stress, and these effects are not modulated by BMI.

Perceived exertion (RPE) increased markedly after the exercise protocol in both groups, with post-exercise values that were higher than pre-exercise values. However, no significant differences were found between the two groups. This finding is consistent with previous results indicating that, although individuals with higher BMI may experience higher cardiovascular and respiratory load during exercise, subjective perception of exertion tends to increase similarly between individuals with different BMI when adjusting exercise intensity (Haff et al., 1997). Strength levels, measured through the handgrip strength test, showed significant differences between both groups before the exercise protocol, with the overweight group showing higher strength levels. After the training session, no significant differences were observed in both groups. Results suggest that individuals with higher BMI, who may have greater absolute muscle mass (despite the absence of empirical data on muscle mass levels at this stage, this hypothesis remains conjectural), tend to show higher levels of strength (Tomlinson et al., 2016). We probably did not find significant differences between the two groups due to the hours of exercise practiced by the subjects. This is a hypothesis, and as such, it remains provisional pending further evidence. Being accustomed to a certain level of training, the subjects may already be adapted to these physical demands regardless of their BMI. The absence of significant post-exercise differences could indicate that, despite differences in absolute strength, the ability to adapt to strength training is similar between the two groups when controlling relative training intensity (Holloszy & Coyle, 1984). Measures of jumping performance (Squat Jump, Countermovement Jump and Abalakov Jump) showed no significant differences between the two groups. These results agree with studies that have shown that jumping ability is closely related to power and explosive strength but may be less efficient in individuals

with higher BMI due to the greater body mass they must displace during jumping (Ben Brahim et al., 2023). Both groups showed improvements in jump heights, which affirms the idea that strength training is effective in improving jumping power regardless of BMI (Paavolainen et al., 1999).

The main limitation of this study was the lack of variables of body composition and the hours of training practiced by the subjects. It would be beneficial to include additional variables in future studies to assess body composition, as this also plays an important role in cardiovascular and autonomic modulation health. In addition to BMI, it would be beneficial to consider the ratio of skeletal muscle mass to body fat percentage when assessing physical fitness.

Practical applications

The findings of this study highlight important practical implications for strength training programming, particularly regarding its autonomic impact on recreational athletes with different body compositions. The observed decrease in HRV during training suggests that strength exercises induce acute autonomic stress, which should be considered when designing training programs to optimize recovery and performance. Coaches and practitioners can use HRV monitoring as a tool to assess training load and ensure adequate recovery, preventing excessive autonomic fatigue, especially in normal-weight athletes who exhibited greater HRV reductions. Moreover, given that overweight athletes demonstrated better strength levels and potentially greater adaptability to strength training, individualized training programs could leverage this advantage by incorporating progressive overload strategies tailored to their physiological responses. The use of HRV-based biofeedback and wearable heart rate monitors may also help athletes regulate their training intensity and recovery strategies more effectively. Incorporating strength training into structured fitness programs for individuals with different BMI classifications can contribute to long-term cardiovascular and neuromuscular adaptations. Future research should focus on the chronic effects of strength training on HRV across diverse populations to further refine training prescriptions and optimize health and performance outcomes.

CONCLUSION

This study aimed to analyse differences in autonomic modulation between normal-weight and overweight young recreational athletes in strength training. The results showed that both groups experienced a reduction in HRV during training, indicating increased autonomic stress. However, the normal-weight group exhibited a greater decrease in HRV, suggesting a higher physiological demand. Additionally, the overweight group demonstrated higher pre-test strength levels, indicating better baseline muscular capacity. These findings suggest that body composition influences autonomic and performance responses to strength training, with overweight athletes potentially exhibiting better adaptability. Future research should further explore the chronic effects of strength training on HRV to optimize training strategies based on BMI classifications.

AUTHOR CONTRIBUTIONS

ÁB-S: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing – original draft, writing – review & editing. SDLT: conceptualization, investigation, methodology, software, writing – original draft, writing – review & editing. VC-S: conceptualization, investigation, validation, writing – original draft, writing – review & editing.

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No potential conflict of interest was reported by the authors.

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Dynamics of collective organization during and across successive momentum phases in elite football matches

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ABSTRACT

Purpose: Recent research (Gautier et al., 2024) has identified collective organization patterns associated with momentum phases in elite football. However, how these patterns evolve remains unknown. The present study aimed to identify their dynamics during momentum phases and across their succession in football matches. **Method(s):** Based on expert coaches' video-based descriptions of football teams experiencing positive than negative momentum (or vice versa) phases, qualitative patterns were classified according to score evolution. **Results:** Over the positive-then-negative momentum scenario, the frequency of patterns of "stretched block", "disconnected actions", "ball carrier far from direct opponent," and "backward defensive runs" increased, whereas the frequency of patterns of "forward block", and "compact block" decreased. Over the negative-then-positive momentum scenario, the frequency of patterns of "connected actions," "defenders close to the ball carrier", and "forward offensive and defensive runs" increased, whereas the frequency of patterns of "compact block", "forward block", "forward offensive runs", and "forward defensive runs" exhibited an increase that began even before the momentum phase transition. **Conclusion(s):** These findings suggest that some patterns may act as precursors or triggers of momentum transitions. Whatever the answer, these patterns can be used by coaches and players as warning signals of impending momentum transition.

Keywords: Behavioural dynamics, Collective organization, Momentum, Qualitative analysis, Team sports.

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INTRODUCTION

In sport, momentum is a multidimensional dynamics that is highly sensitive to the history of ongoing events (Gernigon et al., 2010). This dynamics, whether positive or negative, involves cognitive, affective, motivational, and physiological dimensions, as well as the behavioural responses of athletes experiencing it (Taylor & Demick, 1994). Research that has explored the relationships between momentum and athletic performance mainly focused on the individual experience of momentum (e.g., Briki et al., 2012a; Briki et al., 2012b; Briki et al., 2013; Briki et al., 2014; Den Hartigh & Gernigon, 2018; Den Hartigh et al., 2016; Gernigon et al., 2010; Perreault et al., 1998; Vallerand et al., 1988). In contrast, collective momentum, or team momentum, remains understudied.

Adopting a collective unit of analysis implies considering a team “as an aggregate organism whose behaviour is functionally similar to that of an individual subject” (Mace, Lalli, Shea, & Nevin, 1992, p. 662). Taylor and Demick (1994) proposed a multidimensional cascade model of momentum applicable to both individual athletes and teams. According to this model, specific in-game events trigger cognitive, affective, and physiological changes, which in turn alter players' behaviour, subsequently influencing the performance of both their team and the opposing team, in opposite directions. Events such as game interruptions (Weimer et al., 2023) and score changes (Den Hartigh et al., 2020; Jones & Harwood, 2008; Taylor & Demick, 1994) have been identified as major determinants of the experience of team momentum in sports. While the relationship between such events and team momentum experience is becoming well documented, how this experience translates into collective behaviour remains underexplored.

A few studies have qualitatively highlighted the impact of unfavourable score evolution on intra-team interactions during collective collapse (Apitzsch, 2009; Wergin et al., 2018). Den Hartigh et al. (2014) investigated the effects of positive and negative momentum experiences on interpersonal synchronization within rowing dyads experimentally placed in competition against virtual opponent dyads on ergometers. Positive and negative momentum were associated with increased and decreased rowers' perception of cohesion, respectively. Behaviourally, synchronization within dyads was lower and less stable in the negative momentum condition than in the positive momentum conditions. While these findings provide initial insights into the effects of momentum experiences on synchronization and cohesion within teams, their limitation to dyadic interactions calls for extending the investigation to collective organization in team sports.

In a recent study (Gautier et al., 2024), patterns of collective organization in elite football teams were qualitatively identified as specific to positive or negative momentum experiences defined as significant and gradual score variations. These organizational patterns were classified into three levels: macroscopic (global team level), mesoscopic (within-line player groups), and microscopic (individual players). Key findings revealed that positive momentum phases were associated with a team block (i.e., position of the players of a team without the goalkeeper) that was compact (i.e., lines of players close to each other) and forward-positioned (i.e., the spatial arrangement of all players in front of the longitudinal axis of the field), with players often making forward runs (i.e., without-the-ball runs toward the opponent's goal) both when their team is in possession of the ball (offensive phase) and when their team is not in possession of the ball (defensive phase).

Conversely, negative momentum phases were linked to a stretched (i.e., lines of players far to each other) and backward-positioned (i.e., the spatial arrangement of all players behind the longitudinal axis of the field) team block, frequent defensive backward runs (i.e., without-the-ball runs toward one's goal) and

disconnected individual actions (i.e., Action of players unrelated to the action of other players in the same line).

The results from Gautier et al. (2024) were derived from comparisons between different grouped phases of positive momentum and grouped phases of negative momentum. As such, they did not address one of the most distinctive properties of momentum: its dynamic nature (Gernigon et al., 2010). How collective organization patterns evolve within a team during the development of a single type of momentum or across transitions between types of momentum (e.g., from positive to negative or vice versa) remains unexplored. The present study, a follow-up to Gautier et al.'s (2024), aims to identify the dynamics of collective organization in elite football teams during the development of positive momentum phases followed by negative momentum phases (or vice versa). Using an exploratory approach and consistent with Gautier et al. (2024), collective organizational patterns at macroscopic, mesoscopic, and microscopic levels will serve as reference frameworks for identifying variations throughout gradual and temporal score developments.

In teams experiencing a positive-to-negative momentum sequence (PM-NM sequence), patterns identified by Gautier et al. (2024) as associated with positive momentum were expected to increase in frequency over the positive momentum phase and then decrease until disappearing over the negative momentum phase. The patterns concerned are forward block, compact block, connected actions (i.e., Action of players unrelated to the action of other players in the same line), defenders close to the ball carrier, forward offensive and defensive runs. Conversely, patterns previously identified as associated with negative momentum were expected to appear and then increase in frequency only over the negative momentum phase. The patterns concerned are backward block, stretched block, disconnected actions, defenders far from the ball carrier, backward offensive and defensive runs. The opposite dynamics were expected for teams experiencing a negative-to-positive momentum sequence (NM-PM sequence).

MATERIALS AND METHODS

Participants

The present study covers the two international matches featuring significant comebacks examined by Gautier et al. (2024). One match was the 2005 UEFA Champions League final between AC Milan and Liverpool FC, where Liverpool won in a penalty shootout after recovering from a 0-3 deficit to 3-3. The other match was a 2012 World Cup qualifier between Germany and Sweden, which ended in a 4-4 draw after Sweden overcame a 0-4 deficit. A total of 56 male professional players participated in these matches. In Gautier et al. (2024), patterns of collective organization associated with positive and negative momentum phases were identified and counted from match videos by four expert football coaches. For the present study, these qualitative data were reorganized based on the score evolution of each team by the first author, a former professional football player and expert football coach. This reorganization, based on previously identified data, minimizes subjectivity.

Procedure

The data used were the patterns of collective organization identified at macroscopic, mesoscopic, and microscopic levels by Gautier et al. (2024). For this study, these data were categorized by their occurrence timing and classified according to each match's score evolution.

RESULTS

Occurrences of collective organization patterns are presented separately for PM-NM (AC Milan and Germany) and NM-PM (Liverpool FC and Sweden) scenarios.

PM-NM Scenario

For both PM-NM teams, some patterns were either absent or exhibited no specific temporal differentiation. Such is the case for the "*connected action*" pattern which was not detected for either AC Milan nor Germany. The "*defenders close to the ball carrier*" pattern was not observed for AC Milan but was detected for Germany during the positive momentum phase. Similarly, the pattern "*backward offensive run*" did not appear for AC Milan but occurred during both positive and negative momentum phases for Germany.

Other patterns showed temporal differentiation over the course of the PM-NM sequence, but only for one of the two PM-NM teams. Such is the case for the "*backward block*" pattern which increased in frequency for AC Milan by the end of the positive momentum phase to become prevalent during the negative momentum phase, while its occurrences remained relatively stable across momentum phases for Germany.

Some patterns exhibited opposing distributions between the two teams. The frequency of "*forward offensive runs*" decreased from the positive momentum phase to the negative momentum phase for AC Milan, while it increased during the same transition for Germany.

Table 1A. AC Milan. Summary of the occurrences and temporal distributions of organizational patterns for the two PM-NM teams.

Levels of Collective Organization		Positive Momentum (n)			Negative Momentum (n)	
Dimensions	Themes					
Scoring		1/0	2/0	3/0	3/2	3/3
Timing		0'-1'	30'-44'	45'-53'	54'-59'	60'-75'
Macroscopic Level						
Longitudinal position of the team block						
Forward Block						
Backward Block						
Mesoscopic Level						
Team Block Compactness						
Compact Block						
Stretched Block						
Team Block Connectivity						
Connected Actions						
Disconnected Actions						
Microscopic Level						
Ball Carrier – Nearest Opponent Distance						
Ball Carrier Close to Direct Opponent						
Ball Carrier Far from Direct Opponent						
Without-ball Offensive Runs						
Toward Attacked Goal						
Non-goal-oriented Runs						
Toward Defended Goal						
Without-ball Defensive Runs						
Toward Attacked Goal						
Non-goal-oriented Runs						
Toward Defended Goal						

Table 1B. Germany. Summary of the occurrences and temporal distributions of organizational patterns for the two PM-NM teams.

Levels of Collective Organization		Positive Momentum (n)				Negative Momentum (n)			
Dimensions									
Themes									
Scoring		1/0	2/0	3/0	4/0	4/1	4/2	4/3	4/4
Timing		0'-8'	9'-15'	30'-45'	46'-62'	63'-64'	65'-76'	77'-89'	90'-93'
Macroscopic Level									
<i>Longitudinal position of the team block</i>									
Forward Block			1	3					
Backward Block				1	2		1	1	
Mesoscopic Level									
<i>Team Block Compactness</i>									
Compact Block			1	3					
Stretched Block						1	15	6	
<i>Team Block Connectivity</i>									
Connected Actions									
Disconnected Actions							6	22	
Microscopic Level									
<i>Ball Carrier – Nearest Opponent Distance</i>									
Ball Carrier Close to Direct Opponent			3	1					
Ball Carrier Far from Direct Opponent						5	1	12	
<i>Without-ball Offensive Runs</i>									
Toward Attacked Goal							1		
Non-goal-oriented Runs							2	6	
Toward Defended Goal					1			1	
<i>Without-ball Defensive Runs</i>									
Toward Attacked Goal			3	2					
Non-goal-oriented Runs						4	2	6	
Toward Defended Goal							2		

Some patterns increased in frequency from the positive momentum phase to the negative momentum phase. For both AC Milan and Germany, the occurrences of "*stretched block*," "*disconnected actions*," "*ball carrier far from direct opponent*," and "*backward defensive runs*" were either absent or rare during the positive momentum phase but became increasingly frequent and sometimes numerous during the negative momentum phase.

Finally, some patterns decreased in frequency during the PM-NM sequence. For both AC Milan and Germany, the "*forward block*" pattern was observed only during the positive momentum phase. Similarly, the "*compact block*" pattern was more frequently observed during the positive momentum phase than during the negative momentum phase for both teams. Furthermore, the decline in occurrences of certain patterns sometimes began by the end of the positive momentum phase and continued during the negative momentum phase. This is the case for "*forward defensive runs*", which were most frequent at the start of the positive momentum phase for both AC Milan and Germany, but became increasingly rare, disappearing entirely by the end of the positive momentum phase or the beginning of the negative momentum phase.

NM-PM Scenario

For both NM-PM teams, no occurrences of the pattern "*backward offensive runs*" were observed. Some patterns showed an increase in frequency from the negative momentum phase to the subsequent positive momentum phase. For both Liverpool FC and Sweden, the occurrences of the patterns "*connected actions*," "*defenders close to the ball carrier*", increased during the transition from negative to positive momentum phases.

Table 2A. Liverpool FC. Summary of the occurrences and temporal distributions of organizational patterns for the two NM-PM teams.

Levels of Collective Organization		Negative Momentum (n)			Positive Momentum (n)		
Dimensions	Themes						
Scoring		0/1	0/2	0/3	2/3	3/3	3/3
Timing		0'-1'	30'-44'	45'-53'	54'-59'	60'-75'	76'-90'
Macroscopic Level							
<i>Longitudinal position of the team block</i>							
Forward Block					3	2	
Backward Block		4			4		
Mesosopic Level							
<i>Team Block Compactness</i>							
Compact Block					1	6	
Stretched Block		7			4		
<i>Team Block Connectivity</i>							
Connected Actions					1	2	2
Disconnected Actions		11			8		
Microscopic Level							
<i>Ball Carrier – Nearest Opponent Distance</i>							
Ball Carrier Close to Direct Opponent					4	1	
Ball Carrier Far from Direct Opponent		13			1		
<i>Without-ball Offensive Runs</i>							
Toward Attacked Goal		1			1	5	
Non-goal-oriented Runs		7			3		
Toward Defended Goal							
<i>Without-ball Defensive Runs</i>							
Toward Attacked Goal		1			1	3	
Non-goal-oriented Runs		3			5		
Toward Defended Goal		3			2		

Table 2B. Sweden. Summary of the occurrences and temporal distributions of organizational patterns for the two NM-PM teams.

Levels of Collective Organization		Negative Momentum (n)				Positive Momentum (n)			
Dimensions	Themes								
Scoring		0/1	0/2	0/3	0/4	1/4	2/4	3/4	4/4
Timing		0'-8'	9'-15'	30'-45'	46'-62'	63'-64'	65'-76'	77'-89'	90'-93'
Macroscopic Level									
<i>Longitudinal position of the team block</i>									
Forward Block					2	3	7		
Backward Block		8			2				
Mesosopic Level									
<i>Team Block Compactness</i>									
Compact Block					2	1	6	2	
Stretched Block					1				
<i>Team Block Connectivity</i>									
Connected Actions							3	2	
Disconnected Actions		9			14	1	3		
Microscopic Level									
<i>Ball Carrier – Nearest Opponent Distance</i>									
Ball Carrier Close to Direct Opponent						3	8	3	
Ball Carrier Far from Direct Opponent		13			14				
<i>Without-ball Offensive Runs</i>									
Toward Attacked Goal					1	1	17	9	
Non-goal-oriented Runs		7							
Toward Defended Goal									
<i>Without-ball Defensive Runs</i>									
Toward Attacked Goal					2	4	11	13	
Non-goal-oriented Runs		4			6	1			
Toward Defended Goal					5				

Other patterns exhibited an increase in frequency even before the momentum phase transition. Occurrence of patterns "*compact block*", "*forward block*" and "*forward offensive and defensive runs*" for both Liverpool FC and Sweden began to increase during the negative momentum phase, and this trend continued or even intensified during the subsequent positive momentum phase.

Some patterns, however, saw their occurrences decrease from the negative momentum phase to the positive momentum phase for both teams. Specifically, for Liverpool FC and Sweden, the occurrences of the patterns "*backward block*", "*stretched block*", "*disconnected actions*", "*ball carrier far from direct opponent*", and "*backward defensive runs*" declined significantly or disappeared entirely during the transition from the negative to the positive momentum phase.

DISCUSSION

The aim of the present study was to identify the dynamics of collective organization in elite football teams during the development of positive (or negative) momentum phases and across the succession of opposing momentum phases (from positive to negative or vice versa). For some collective organizational patterns, it was not possible to interpret typical evolutions due to either the absence of occurrences (e.g., PM-NM scenarios: "*ball carrier close to direct opponent*"; NM-PM scenarios: "*backward offensive runs*") or a limited number of changes in occurrences (e.g., PM-NM scenarios: "*backward block*", "*backward offensive run*", and "*non-goal-oriented offensive runs*"), or divergent evolutionary trends between the two teams experiencing the same momentum sequence (e.g., "*forward offensive runs*"). However, other collective organizational patterns, whether macroscopic, mesoscopic, or microscopic, exhibited interpretable dynamics.

The backward-positioned block, a macroscopic collective organizational pattern, emerged even when the team led significantly during the positive momentum phase and persisted over the subsequent negative momentum phase. This positioning, characterized by Gautier et al. (2024) as typical of negative momentum phases, can be interpreted as a behavioural manifestation of a team's defensive intentions (Gréhaigne et al., 1997). Such positioning is commonly observed in teams facing superior opponents (Fernandez-Navarro et al., 2018; Vogelbein et al., 2014). Thus, the leading team behaves as if its opponent were superior.

Regarding mesoscopic collective organizational patterns, the "*stretched block*" showed a notable increase during PM-NM scenarios. The widening of distances between players is a marker of team disorganization, as evidenced by Folgado et al. (2012). Similarly, "*disconnected actions*" increased during this transition. These uncoordinated player actions reflect the team's difficulty in functioning as an integrated unit (Araujo & Bourbousson, 2016), likely due to breakdowns in verbal and non-verbal communication between players (Higham & Harwood, 2005).

Furthermore, ineffective microscopic collective organizational patterns emerged during the PM-NM scenario. For example, the increase in defensive patterns such as "*ball carrier far from direct opponent*" highlights this trend, as defensive players distanced themselves from the ball carrier, allowing them greater freedom to initiate offensive actions. This passivity facilitates scoring opportunities for the opposing team (González-Rodenas et al., 2016). Similarly, "*backward defensive runs*" increased, which reflects defenders' retreat toward their own goal and reduce their ability to recover the ball and launch counterattacks effectively (Cooper & Pulling, 2020; González-Rodenas et al., 2016; Hughes & Lovell, 2019). Finally, the increase in backward defensive runs during the PM-NM scenarios caused the team block to adopt a lower position on the field. Despite still leading in the score, the team adopted a defensive posture, with players retreating and failing to advance into the field of play (Higham & Harwood, 2005). This behaviour may reflect intentions such as

performance-avoidance goals that have been found to be associated with negative momentum experiences (Briki et al., 2012). However, the appearance of this pattern at the end of positive momentum phases (i.e., when the team leads significantly) is surprising. It could either be a warning signal of the impending momentum reversal or one of its triggering factors, as highly positive momentum might lead players to relax their offensive pressure, feeling secure against a comeback (Higham & Harwood, 2005).

When the negative momentum phase was followed by a positive momentum phase within the same match, the forward-positioned team block—a macroscopic organizational pattern—emerged at the end of the negative momentum phase and became more frequent during the subsequent positive momentum phase. This observation corroborates the findings of Gautier et al. (2024), who showed that a forward-positioned team block was specific to positive momentum phases and could represent a behavioural manifestation of a team's offensive intentions (Gréhaigne et al., 1997). Such intentions, in the form of performance-approach goals, have been found to be linked to positive momentum experiences (Briki et al., 2012; Gernigon et al., 2010). These observations also apply to microscopic organizational patterns, particularly with respect to the direction of defensive runs. Players started to move forward on the pitch when defending in the initial negative momentum phase and did so even more during the following positive momentum phase, thus exerting pressing on the opposing team to disrupt their play construction (Frencken et al., 2012). This result, consistent with the findings concerning forward-positioned team blocks, aligns with Gautier et al.'s (2024) observations, which evidenced an association between forward-oriented runs and positive momentum experiences. It also confirms that offensive intentions, for instance in the form of performance-approach goals, are typically associated with positive momentum experiences (Briki et al., 2012; Gernigon et al., 2010). The added value brought by the present finding is that, in team sports, this happens even when a team does not possess the ball.

The anticipated occurrence—toward the end of negative momentum—of a forward-positioned team block raises questions about its status as a precursor or a triggering factor for the momentum transition. This issue also applies to block compactness. Compact team blocks occasionally appeared during the negative momentum phase, developing more prominently in the subsequent positive momentum phase. While Gautier et al. (2024) showed the association between compact blocks and positive momentum experiences, the occurrence dynamics of this pattern reveals a progression that begins before the appearance of the positive momentum phase. This raises questions about its role in momentum transitions.

In summary, the present findings indicate that collective organizational patterns evolve differently based on score progression within momentum phases and across successive momentum phases experienced by teams. While adaptive behavioural patterns appeared more frequently during positive momentum phases, as reported by Gautier et al. (2024), these patterns were often present, to a lesser extent, at the end of the preceding negative momentum phase. Conversely, a few maladaptive patterns were observed at the end of positive momentum phases and subsequently developed during negative momentum phases.

Several interpretations can be explored to explain the anticipatory nature of some behavioural patterns for upcoming momentum phases. First, the presence of a pattern typically associated with the opposite momentum type during a given phase could signify an early manifestation of a new momentum phase. Alternatively, the early appearance of such a pattern might indicate a causal relationship, with the pattern acting as a trigger for the new momentum type. In both cases, the momentum experience would not be strictly demarcated by score variations but would begin before the first score reduction. Instead, score progression might serve as a possible consequence of an already initiated momentum phase. Therefore, this hypothesis challenges the commonly accepted notion that score evolution is a key determinant of momentum

experiences (e.g., Briki et al., 2012; Jones & Harwood, 2008; Taylor & Demick, 1994). While a goal scored against the run of play could plausibly trigger momentum, it is likely that in the amplifying spiral of momentum experiences (Briki et al., 2012), score evolution functions as both an antecedent and a consequence of momentum.

Beyond the question of whether the egg (scoring) or the chicken (the momentum experience) comes first, counterfactual behavioural patterns relative to an ongoing momentum phase may correspond to reactions to that phase. For example, the occurrence of adaptive patterns during a negative momentum phase preceding a positive momentum phase could reflect phenomena such as negative facilitation (Cornelius et al., 1997; Perreault et al., 1998; Silva et al., 1988) or reactance (Brehm, 1972). Negative facilitation involves increased effort to compensate for a temporary failure, while reactance corresponds to an effort to regain control over a situation perceived as slipping away. Both negative facilitation and reactance have been observed during negative momentum experiences in sports settings (Briki et al., 2012; Briki et al., 2013; Perreault et al., 1998).

Conversely, the occurrence of maladaptive patterns during a positive momentum phase preceding a negative momentum phase could reflect phenomena such as positive inhibition (Silva et al., 1988) or coasting (Carver, 2003). These involve a form of relaxation stemming from the perception that substantial progress has been made toward achieving a goal, rendering its attainment seemingly inevitable. This relaxation phenomenon, which can negatively impact performance (Adler, 1981), has also been observed during positive momentum experiences in sports (Briki et al., 2012; Briki et al., 2013; Perreault et al., 1998).

From an applied perspective, regardless of the hypothesis adopted to explain the presence of counterfactual patterns during a momentum phase, these patterns can serve as warning signals for players and coaches about an impending momentum transition. On one hand, recognizing behavioural patterns indicative of an upcoming positive momentum phase can facilitate a psychological transition toward cognitive (e.g., attention, efficacy beliefs), affective (e.g., hope), and motivational states (e.g., effort intentions, determination) conducive to adaptive behavioural modifications (e.g., increased effort, improved interpersonal coordination). On the other hand, recognizing behavioural patterns that signal an impending negative momentum phase can highlight the need to intensify efforts to maintain adaptive states. Identifying these counterfactual patterns thus constitutes a valuable help for both coaches' and players' decision-making and behaviour-change (Higham et al., 2005). The ability to recognize these patterns is a skill that should be specifically developed through training.

CONCLUSION

This study is the first to examine the evolution of collective organizational patterns in teams experiencing two distinct momentum phases (positive and negative) within a single football match. The primary limitation of this research lies in the difficulty of obtaining exploitable video footage of matches featuring such scenarios, resulting in a small sample size ($n = 4$) of analysed teams. Consequently, the findings should currently be interpreted within the context of these matches and cannot be generalized. Replicating this study with other teams experiencing both comeback and collapse scenarios in the same match would help confirm or refute the observed trends. Additionally, the present study focused on the objective (scoring) and behavioural dimensions of momentum (Hubbard, 2015). Behavioural momentum has often been shown to precede objective momentum. In future research, it would be interesting to examine whether a team's behavioural momentum experience is itself preceded by psychological momentum experiences at the individual player level (Hubbard, 2015).

AUTHOR CONTRIBUTIONS

Gautier, Cavailles and Gernigon wrote the paper and collected the data. All authors approved the final submission.

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Integrating multimodal AI technologies for sports injury prediction and rehabilitation: Systematic review

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ABSTRACT

Traditional methods for sports injury prevention and rehabilitation rely predominantly on subjective clinician-guided assessments and standardized intervention protocols. These approaches often result in limited accuracy, delayed responsiveness, and insufficient personalization. Recent advances in artificial intelligence (AI), wearable sensor technologies, and multimodal analytics provide novel opportunities for objective, real-time, and personalized injury management strategies. Despite these advances, there remains a critical need for systematic synthesis and evaluation of integrated multimodal approaches. This systematic review critically evaluates contemporary developments in multimodal AI technologies applied specifically to sports injury prediction and rehabilitation. We systematically describe the biomechanical and physiological foundations of common acute and chronic sports injuries and present them within an integrated, five-stage injury recovery pipeline. Our analysis emphasizes AI methods including sensor fusion frameworks, time-series classification algorithms, and predictive analytics that enhance early injury detection, accurate risk modelling, and timely interventions. For the rehabilitation phase, we critically assess AI-supported motion quality assessment methods, adaptive feedback mechanisms, and individualized recovery protocols facilitated by wearable and vision-based technologies. Furthermore, we evaluate the real-world deployment and athlete-specific modelling strategies of AI systems, addressing challenges of environmental robustness, computational efficiency, and personalized adaptation. Multimodal AI technologies offer substantial potential for revolutionizing sports injury prediction and rehabilitation by enabling highly individualized, data-driven, and context-aware solutions. Nevertheless, significant challenges persist in the areas of model generalization, interpretability, privacy concerns, and clinical validation. Promising future research directions include the advancement of explainable AI frameworks, digital twin technologies, and multi-agent modelling approaches, aimed at overcoming these limitations and advancing personalized, intelligent sports medicine.

Keywords: Artificial intelligence, Sports injury prediction, Rehabilitation monitoring, Multimodal sensors, Sensor fusion, Predictive analytics, Explainable AI, Personalized feedback, Edge computing.

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INTRODUCTION

Injury prevention and rehabilitation are critical components of modern sports science and athlete management. Sports-related injuries not only compromise athletic performance and career longevity but also impose significant economic and psychological burdens on individuals and institutions. Traditional approaches to injury risk assessment and post-injury rehabilitation often rely on manual observation, subjective clinical judgment, or basic biomechanical evaluations—methods that may lack sensitivity, scalability, and real-time responsiveness (Arzehgar et al., 2025). In recent years, artificial intelligence (AI) has emerged as a promising solution to overcome these limitations by offering data-driven, adaptive, and intelligent support across the full spectrum of injury management (Reis, Alaiti, Vallio, & Hespanhol, 2024; Van Eetvelde, Mendonça, Ley, Seil, & Tischer, 2021).

The proliferation of AI in sports injury science is driven by several factors. First, advances in computer vision, machine learning, and wearable sensor technology have enabled the collection and interpretation of large-scale, multimodal datasets, including kinematic, kinetic, physiological, and environmental information (Cao, Hidalgo, Simon, Wei, & Sheikh, 2021; Picerno, 2017). Second, AI algorithms, particularly those based on deep learning and time-series modelling, have shown the ability to uncover subtle patterns and temporal trends that correlate with increased injury risk or suboptimal recovery trajectories (Hannink et al., 2017; Sadr, Khani, & Tootkaleh, 2025). Third, the emergence of real-time inference platforms and edge AI devices has opened new opportunities for on-field monitoring and closed-loop rehabilitation systems (Sabry, Eltaras, Labda, Alzoubi, & Malluhi, 2022).

This review aims to provide a comprehensive overview of AI-driven approaches for injury prevention and rehabilitation in sports. We structure our discussion around three core pillars of injury management: (1) early prediction and risk modelling, (2) AI-assisted rehabilitation monitoring, and (3) intelligent feedback and personalization. For each area, we analyse representative algorithms, system architectures, and clinical deployment scenarios, with a particular focus on sports-specific datasets, evaluation metrics, and real-world applications.

Furthermore, this review highlights the integration of AI with wearable technologies, such as inertial measurement units (IMUs), electromyography (EMG), and pressure sensors, as well as the rise of digital twin frameworks that simulate and monitor the recovery process (Gu, Lin, He, Zhang, & Zhang, 2023; Hliš, Fister, & Fister Jr, 2024). We also identify key technical challenges—including inter-subject variability, data heterogeneity, model interpretability, and clinical validation—that currently limit the adoption of AI in sports healthcare (Lundberg & Lee, 2017).

By synthesizing current research and projecting future directions, this work intends to serve as a foundational reference for interdisciplinary researchers and practitioners working at the intersection of sports medicine, movement science, rehabilitation engineering, and artificial intelligence. Ultimately, the goal is to facilitate the development of intelligent, personalized, and effective systems for injury prevention and recovery, contributing to safer and more sustainable athletic performance.

OVERVIEW OF SPORTS INJURIES AND RECOVERY PIPELINE

Sports injuries remain a significant concern across all levels of athletic participation, impacting not only physical performance but also psychological well-being and long-term health outcomes. These injuries may occur acutely, as a result of trauma, or develop chronically through repetitive stress and suboptimal

biomechanical patterns. As injury rates continue to rise in both amateur and professional sports, there is an urgent need to enhance our understanding of injury mechanisms and optimize the recovery process through data-informed and intelligent solutions. In this context, artificial intelligence (AI) has emerged as a powerful tool for improving injury risk prediction, rehabilitation monitoring, and return-to-sport assessment (Musat et al., 2024).

Common types of sports injuries

Sports-related injuries are generally categorized into two types: acute and chronic. Acute injuries typically result from sudden impact or trauma, leading to conditions such as ligament ruptures—most notably anterior cruciate ligament (ACL) tears—muscle strains, joint dislocations, and bone fractures. These events often require immediate medical attention and structured rehabilitation (B. Y et al., 2025). Chronic injuries, in contrast, develop gradually due to repeated mechanical loading or improper training. Common examples include Achilles tendinopathy, patellofemoral pain syndrome, stress fractures, and overuse-related shoulder or knee issues. These injuries are often harder to detect in early stages and may result in long-term movement impairments if not properly managed (Guo, Liu, & Li, 2024). Understanding these injury types provides the clinical and biomechanical basis for designing AI-supported assessment and intervention tools. AI-driven platforms can leverage diagnostic markers and recovery patterns to inform tailored rehab protocols (Kaur et al., 2020).

Building on our discussion of the clinical and biomechanical underpinnings of sports injuries, Table 1 distills the most prevalent injury types into a structured overview. It aligns each injury—ranging from acute events like ACL ruptures to chronic conditions such as stress fractures—with its characteristic mechanism, hallmark clinical signs, and standard assessment modalities. This consolidated snapshot not only reinforces the five-stage recovery pipeline but also highlights where objective, AI-driven tools can most effectively intervene during early detection and diagnostic evaluation.

Table 1. Key sports injury types and clinical characteristics.

Injury type	Mechanism	Clinical signs	Standard assessment
ACL rupture	Non-contact pivot	Knee instability, pain	Lachman test, MRI
Muscle strain	Overstretch/tear	Localized pain, swelling	Palpation, ultrasound
Patellofemoral pain	Overuse, malalignment	Anterior knee pain	Clinical exam, gait analysis
Stress fracture	Repetitive load	Localized bone tenderness	Bone scan, MRI

This table contrasts common acute and chronic sports injuries by mechanism, hallmark clinical signs, and typical assessment modalities, providing a quick reference for the pipeline stages described in next section.

The sports injury recovery pipeline

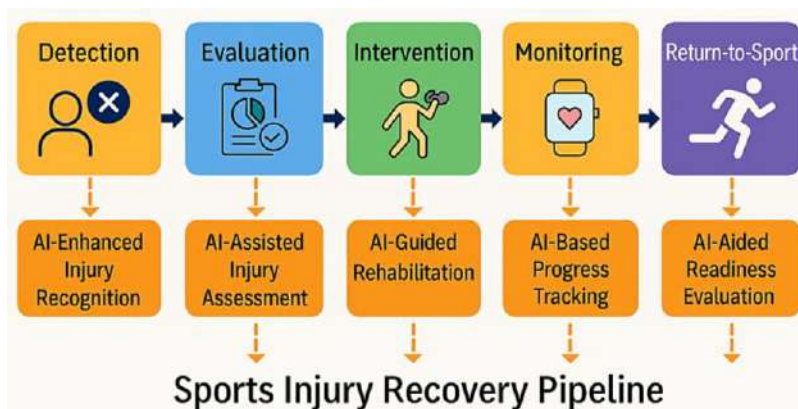
The sports injury recovery process is typically structured as a multi-phase pipeline encompassing detection, evaluation, intervention, monitoring, and reintegration. The first phase involves the recognition and localization of the injury, traditionally based on physical examination, medical imaging, and patient-reported symptoms. In many cases, diagnosis may be delayed or imprecise due to the subjective nature of evaluation. However, AI-assisted diagnostic systems can enhance precision by automatically classifying injury severity based on imaging and motion data (Andriollo et al., 2024). The second phase centres on injury profiling and severity assessment, where clinicians measure range of motion, strength, and movement deficits. AI-based systems are increasingly utilized here to analyse motion asymmetries, segmental imbalances, and sensor-derived patterns that may not be visible to the naked eye (Musat et al., 2024).

Rehabilitation constitutes the third phase and often includes a combination of therapeutic exercises, neuromuscular re-education, and proprioceptive training. AI can play a key role in this stage by providing intelligent feedback on exercise form, dynamically adjusting difficulty levels, and optimizing recovery trajectories based on individual response (Amendolara et al., 2023). The fourth phase introduces continuous monitoring and feedback loops, wherein wearables or computer vision-based systems capture ongoing motion data to prevent compensation patterns and identify signs of reinjury (Ramkumar et al., 2022). Finally, the return-to-sport phase entails decision-making about an athlete's readiness to re-enter competitive environments. Here, AI classifiers trained on longitudinal performance data and risk factors can assist practitioners in making objective and personalized judgments (Yung, Wu, Aus der Fñnten, Hecksteden, & Meyer, 2025). Radiomics-based systems have demonstrated over 90% accuracy in predicting time to return-to-play (Desai, 2024).

This pipeline is not strictly linear; instead, it reflects a feedback-rich cycle where monitoring and assessment can trigger earlier re-entry into rehabilitation when necessary. Integrating AI at each stage enables the system to adapt in real time to the athlete's evolving physiological state, thereby improving the efficiency and safety of the recovery process (Leong, Leong, & Leong, 2024).

Limitations of traditional methods

Despite the sophistication of modern sports medicine, traditional approaches to injury prevention and rehabilitation often suffer from critical limitations. Clinical assessments are inherently subjective, with outcomes heavily dependent on practitioner experience and consistency. Data collection is frequently episodic and delayed, reducing opportunities for timely intervention. Moreover, rehabilitation protocols are often designed in a generalized fashion, without accounting for individual differences in anatomy, training history, or responsiveness to therapy (Yung, Arden, Serpiello, & Robertson, 2022). Finally, real-world applicability is limited, as many existing assessment tools are confined to laboratory or clinical settings and do not translate well to dynamic, on-field environments. These constraints highlight the need for AI-enabled systems that are objective, continuous, and capable of delivering real-time, context-aware insights to both athletes and clinicians (Corban et al., 2021).



Note. The framework illustrates five interconnected stages of recovery, from injury onset to reintegration into sport. Embedded AI components provide predictive modelling, automated assessment, intelligent monitoring, and adaptive feedback throughout the recovery cycle.

Figure 1. The sports injury recovery pipeline and AI integration points.

To visually consolidate the discussion in this section, Figure 1 presents a conceptual flowchart of the sports injury recovery pipeline and highlights the potential roles of AI at each stage. The model reflects a non-linear,

feedback-driven process consisting of five key phases: injury detection, evaluation, rehabilitation, monitoring, and return-to-sport assessment. Across this pipeline, AI technologies are embedded to enhance decision-making, personalize recovery trajectories, and enable real-time feedback through sensor analytics, biomechanical modelling, and data-driven planning. This integrated perspective helps contextualize where and how intelligent systems can transform traditional recovery workflows.

AI FOR INJURY RISK PREDICTION AND EARLY DETECTION

Injury risk prediction plays a pivotal role in modern sports science, enabling proactive interventions that reduce injury incidence and improve athlete longevity. Traditional tools such as movement screenings and injury history questionnaires are limited in their predictive power and fail to capture the complex, multifactorial nature of sports injuries. Artificial intelligence (AI) offers a transformative approach, leveraging multimodal data and machine learning models to uncover subtle risk factors and deliver individualized, context-aware assessments (Nechita et al., 2025). This section reviews the primary data sources, modelling techniques, application cases, and challenges associated with AI-based injury prediction in sports.

Multimodal data for risk prediction

A key advantage of AI systems lies in their ability to integrate diverse data streams for comprehensive injury risk assessment. Kinematic and kinetic data, collected through motion capture or wearable inertial sensors, provide detailed information on joint mechanics, asymmetries, and loading patterns—important indicators of musculoskeletal stress (Hudson, Hartigh, Meerhoff, & Atzmüller, 2023). Physiological signals such as heart rate variability (HRV), electromyography (EMG), and muscle oxygenation further reflect fatigue levels and neuromuscular control (Oetl et al., 2025). These data are often supplemented by training loads, recovery logs, sleep metrics, and contextual variables including position played, surface type, or environmental conditions. The integration of such multimodal datasets enhances the robustness and specificity of AI-based risk models (Huang et al., 2022).

Following our examination of multimodal data streams and machine learning architectures for risk modelling, Table 2 clarifies how specific sensor inputs are paired with suitable AI techniques. For example, it shows how IMU kinematic sequences feed into LSTM or Transformer networks to estimate ACL risk (Gai, 2025), while HRV and EMG signals inform SVM-based fatigue indices (W. Li, 2024). By linking each data modality to its typical output metric and a representative sports application, the table makes explicit the end-to-end pathway from raw sensor capture to actionable injury-risk predictions.

Table 2. Data modalities and AI techniques for injury risk modelling.

Modality	AI technique	Typical output	Example use case
IMU kinematics	LSTM, Transformer	ACL risk probability	Running gait analysis
HRV / EMG	SVM, Random Forest	Fatigue index	Overtraining detection
Video (pose)	CNN + GCN	Movement asymmetry score	Jump-landing screening
Training load	XGBoost	Injury likelihood score	Basketball practice load

This table maps key multimodal inputs to the AI algorithms most often used for injury risk prediction, along with their outputs and representative sports applications, complementing the discussion in next section.

Machine learning techniques for injury modelling

A wide range of machine learning algorithms have been applied to injury prediction tasks. Tree-based models (e.g., Random Forest, XGBoost) are popular for their interpretability and performance with structured data

(W. Li, 2024). Support Vector Machines (SVM) are employed in scenarios with high-dimensional but relatively small datasets (Claudino et al., 2019). More recently, neural networks—particularly Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) networks—have gained traction due to their ability to model temporal dependencies in time-series data such as gait dynamics and fatigue evolution (Adetiba, Iweanya, Popoola, Adetiba, & Menon, 2017). Transformer-based models, known for their self-attention mechanisms, are being explored for long-range motion analysis (Rossi, Pappalardo, & Cintia, 2022). These models are typically trained on retrospective injury datasets and evaluated using classification metrics like accuracy, AUC, sensitivity, and specificity. Class imbalance, a common issue due to the relative rarity of injury events, is addressed through resampling, cost-sensitive training, or synthetic data generation (Zhang, Li, Shao, & Wang, 2024).

Practical applications in sports settings

AI-based risk prediction has been successfully implemented in several sports domains. For instance, IMU-driven models have been used to detect gait asymmetries that correlate with ACL injury risk in runners and jump-based athletes (Calderón-Díaz et al., 2024). In team sports such as soccer or basketball, supervised models trained on training load, perceived exertion, and match exposure have shown potential in forecasting overuse injuries like hamstring strains (Speiser et al., 2021). Increasingly, these systems operate in real time, using wearable sensors and cloud-based inference to provide dynamic risk scores and injury likelihood predictions. These insights are used by coaches, trainers, and medical teams to make informed decisions about workload adjustment, rest periods, and rehabilitation scheduling (Tedesco, Scheurer, Brown, Hennessy, & Flynn, 2022).

Challenges and limitations

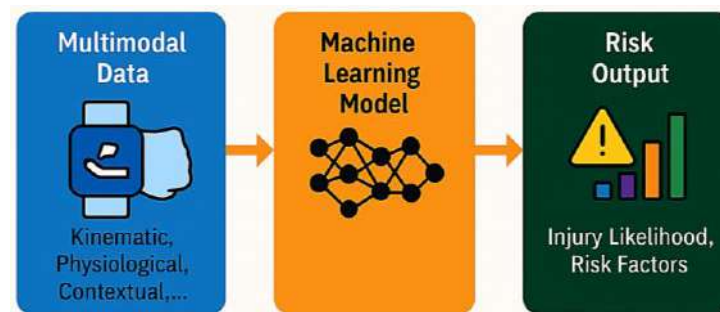
Despite promising developments, several challenges hinder the widespread adoption of AI-based injury prediction systems. Data quality and standardization remain critical bottlenecks, as noise, sensor variability, and inconsistent labelling degrade model performance (Kokkotis et al., 2022). Furthermore, population-specific models may struggle to generalize across sports, age groups, or competition levels (Jauhiainen et al., 2021). A major barrier is the lack of interpretability in deep learning models, which often function as "*black boxes*" and may not provide actionable insights to practitioners. Additionally, issues surrounding data privacy, fairness, and informed consent must be carefully managed, particularly when dealing with sensitive athlete health information.

Toward explainable and personalized prediction

To increase clinical adoption and real-world utility, the future of AI-based injury prediction lies in explainable and personalized systems. Explainable AI (XAI) techniques help interpret model decisions by highlighting influential biomechanical or physiological features, enabling practitioners to understand and trust the output (Mishra, Habal, Garcia, & Garcia, 2024). Personalized modelling, using an athlete's baseline performance and individual characteristics, improves prediction specificity and reduces false positives (Retzepis et al., 2024). Continual learning frameworks—which update model parameters based on ongoing feedback—will further enhance adaptability over time (Sukumar, Zhang, Tao, Wang, & Zhang, 2020). Together, these directions point toward intelligent, athlete-centred systems that actively support injury prevention through early detection and dynamic risk assessment.

To synthesize the key elements discussed in this chapter, Figure 2 illustrates a conceptual pipeline for AI-driven injury risk prediction. The framework begins with multimodal data collection—including motion capture, wearable sensors, physiological measurements, and contextual variables—which serve as input for machine learning algorithms. These models analyse temporal and structural patterns to estimate injury likelihood,

ultimately producing real-time risk assessments that can inform training decisions, recovery planning, and medical interventions. This pipeline emphasizes the role of data integration and intelligent modelling in advancing proactive injury prevention strategies.



Note. Multimodal data sources including biomechanical, physiological, and contextual inputs are processed by machine learning models to generate individualized injury risk assessments.

Figure 2. Conceptual pipeline of AI-driven injury risk prediction in sports.

AI-SUPPORTED REHABILITATION MONITORING AND FEEDBACK

Rehabilitation is a critical phase in the sports injury management pipeline, aimed at restoring function, strength, and movement patterns while minimizing the risk of re-injury. Traditional rehabilitation relies heavily on in-clinic supervision and therapist judgment, which can be limited by subjectivity, resource constraints, and lack of real-time feedback. In this context, artificial intelligence (AI) offers transformative potential to enhance rehabilitation precision, scalability, and personalization. By integrating computer vision, sensor analytics, and adaptive modelling, AI systems can support both clinicians and athletes throughout the recovery process—from motion assessment to intelligent feedback and long-term progress tracking.

Intelligent motion assessment and exercise tracking

One of the primary roles of AI in rehabilitation is the automatic evaluation of exercise execution and movement quality. Using video input or data from wearable sensors, AI models—particularly pose estimation and deep learning-based classifiers—can assess joint angles, movement symmetry, and range of motion during rehabilitation exercises (Jubair et al., 2025). Computer vision systems such as OpenPose or BlazePose are increasingly embedded in mobile applications to allow athletes to perform exercises at home while receiving instant feedback on form correctness (Kandala, V, V, & Palaniswamy, 2024). More advanced systems use sequence models (e.g., LSTM or Transformers) to evaluate temporal consistency and to flag irregular patterns that may indicate compensation strategies or improper load distribution (Poongodi, Kavitha, Sathish, & Lakshmana Kumar, 2025).

Real-Time feedback and adaptive support

Beyond passive assessment, AI systems are capable of delivering real-time, actionable feedback to the athlete. Such feedback may be delivered via visual overlays, auditory cues, or haptic signals, alerting the user when an exercise is performed incorrectly or needs adjustment. These capabilities are particularly useful for home-based or remote rehabilitation, where therapist supervision is limited (Khalid et al., 2024). Some systems also adapt the difficulty or number of repetitions in real time based on performance metrics and fatigue signals, mimicking a form of intelligent virtual coaching (Rasa, 2024). Reinforcement learning-based controllers and adaptive feedback loops are being explored to dynamically tune rehabilitation programs in accordance with recovery trajectories (S. C, B. J. J, A. M, V, & A. S, 2024).

Progress monitoring and recovery analytics

AI-enabled platforms can also serve as comprehensive recovery dashboards, continuously tracking progress over time. By aggregating kinematic data, strength metrics, and subjective reports (e.g., pain levels, confidence scores), machine learning algorithms can model the rate of recovery and detect plateaus or regressions (Nicora et al., 2025). Time-series analysis and anomaly detection models can help flag deviations from expected healing curves (Lanotte, O'Brien, & Jayaraman, 2023). These systems assist clinicians in making evidence-based decisions on progressing or modifying rehabilitation plans. Furthermore, recovery profiles can be benchmarked against population-level data or an athlete’s pre-injury baseline to provide individualized recommendations.

Applications of wearable and vision-based systems

Several practical implementations of AI-supported rehabilitation have emerged in recent years. Wearable technologies—such as IMU suits, smart garments, and EMG-integrated sensors—enable motion capture and muscle activity tracking outside of lab environments (LaBoone & Marques, 2024). When combined with AI models, these platforms can detect key events such as compensatory strategies or load asymmetry in real-world training contexts (Sumner et al., 2023). On the other hand, vision-based systems using RGB or depth cameras allow for marker less motion analysis, making the technology more accessible for clinics and home use. Hybrid solutions are also being explored, fusing video, audio, and bio signal data for robust, multimodal recovery tracking.

Extending from our survey of AI-enabled assessment and feedback mechanisms in rehabilitation, Table 3 compares four classes of rehabilitation platforms—vision-based, wearable IMU, smart garments, and hybrid solutions. It outlines each system’s sensing modalities, feedback channels, real-time capabilities, and deployment contexts. This side-by-side evaluation underscores the trade-offs between immediacy (e.g., haptic cues from wearables) and contextual richness (e.g., combined camera-sensor fusion), guiding readers toward the most appropriate tool for home-based, clinic-based, or elite sports rehabilitation scenarios.

Table 3. Comparison of AI-driven rehabilitation tools.

System type	Sensors	Feedback mode	Real-time?	Deployment context
Vision-based	RGB / depth camera	Visual overlay	Yes	Remote / home rehab
Wearable (IMU)	IMU, sEMG	Haptic, auditory	Yes	Field-based, gym
Smart garments	Strain sensors, pressure	Visual + haptic	Partial	In-clinic, home
Hybrid	IMU + camera + EMG	Multimodal feedback	Yes	Research, elite sport

This table contrasts primary AI rehabilitation platforms, outlining their sensing modalities, feedback channels, real-time capabilities, and deployment contexts, to highlight strengths and limitations discussed in next section.

Limitations and deployment challenges

Despite significant progress, several challenges limit the clinical translation of AI-supported rehabilitation tools. One key issue is model generalization, as AI systems trained on limited or homogeneous datasets may not perform well across diverse populations or injury types (Sardari et al., 2023). Sensor noise, occlusion, and inconsistent lighting can degrade the accuracy of vision-based systems. There are also concerns about data privacy, especially when cloud-based platforms collect sensitive health information. Furthermore, clinicians may be hesitant to rely on “black-box” systems without transparent decision-making processes, underscoring the need for interpretable AI and user-centred interface design (Wani, Kumar, Mamta, Bedi, & Rida, 2024).

To visually convey the role of AI in rehabilitation workflows, Figure 3 presents a simplified feedback loop structure. The system begins with continuous motion tracking via cameras or wearable sensors, followed by real-time assessment of movement quality. Intelligent modules provide immediate feedback to the athlete through auditory or visual signals, while adaptive algorithms dynamically adjust exercise difficulty, duration, or form based on individual performance. This closed-loop structure reflects a transition from static rehabilitation protocols to intelligent, responsive systems capable of supporting safe and efficient recovery.

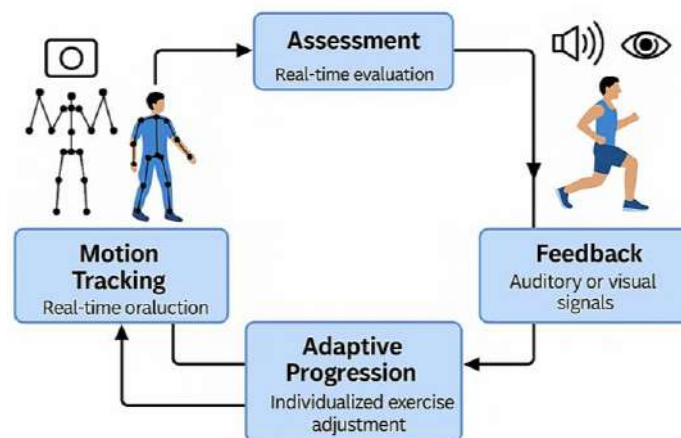


Figure 3. AI-supported rehabilitation feedback loop.

This flowchart illustrates a closed-loop rehabilitation system powered by AI. Motion Tracking (using wearable sensors or vision-based pose estimation) continuously captures exercise movements. Assessment modules then perform real-time evaluation of movement quality and detect compensatory patterns. Based on these insights, Feedback is delivered via auditory, visual, or haptic cues to guide the athlete's form and execution. Finally, an Adaptive Progression engine adjusts exercise difficulty, duration, or repetitions according to performance metrics and fatigue indicators. Arrows denote the continuous exchange of data, enabling dynamic, personalized rehabilitation that adapts as the athlete recovers.

INTEGRATION WITH WEARABLES AND REAL-WORLD DEPLOYMENT

While artificial intelligence (AI) algorithms have demonstrated strong potential in controlled environments, their practical impact in sports injury management critically depends on integration with wearable technologies and deployment in real-world athletic contexts. Bridging this gap requires systems that are not only accurate but also portable, unobtrusive, adaptive, and context-aware. This chapter examines the convergence of AI and wearables, the enabling infrastructure for field-ready deployment, and the key challenges associated with operationalizing such systems in sports environments.

Advances in wearable sensor technologies

Modern wearable systems have evolved far beyond step counters and heart-rate monitors. Current platforms include inertial measurement units (IMUs), surface electromyography (sEMG), pressure-sensing insoles, flexible strain sensors, and smart textiles, capable of capturing rich biomechanical and physiological data in real time. These devices offer a continuous, low-latency stream of data that serves as high-quality input for AI models across risk prediction, rehabilitation monitoring, and feedback generation. For example, multi-sensor garments can detect compensatory gait patterns, asymmetries in joint loading, or improper postural alignments that contribute to injury recurrence (Yadav & Yadav, 2025).

On-device ai and edge computing

To achieve real-time, low-latency feedback in the field, many AI-enhanced systems are being deployed on edge computing devices, such as smartphones, smartwatches, or dedicated AI chips (e.g., NVIDIA Jetson Nano, Apple Neural Engine, Google Edge TPU). These platforms allow motion data to be processed locally, reducing reliance on cloud infrastructure and addressing data privacy concerns. On-device inference also improves system responsiveness, enabling live corrective feedback during rehabilitation exercises or return-to-play assessments. Such architectures are critical for developing mobile, coach-facing, or athlete-facing applications in training centres or on the field (Vijayan, Connolly, Condell, McKelvey, & Gardiner, 2021).

In light of our discussion on integrating AI with wearables and edge computing, Table 4 details the sampling rates, compute requirements, and latency targets for key sensor types—IMUs, sEMG arrays, pressure insoles, and smart textiles—alongside exemplar devices. By specifying microcontroller versus DSP processing needs and acceptable latency thresholds, this table informs the practical design of low-latency, on-device AI inference pipelines that are robust enough for deployment in dynamic, real-world athletic environments.

Table 4. Wearable sensors and edge-AI deployment requirements.

Sensor type	Sampling rate	Compute needs	Latency target	Example device
IMU	100–400 Hz	Low (microcontroller)	< 50 ms	Xsens MVN Link
sEMG	500–2000 Hz	Medium (DSP/CPU)	< 100 ms	Myo armband
Pressure insole	100 Hz	Low	< 100 ms	Loadsol (Novel)
Smart textile	50–100 Hz	Low–Medium	< 200 ms	Hexoskin smart shirt

This table outlines key wearable technologies, their sampling characteristics, and on-device processing requirements, directly informing the edge-AI and deployment considerations in next section.

Contextual adaptation and environmental robustness

Real-world deployment introduces variability in surface type, lighting, noise, clothing, and environmental conditions that challenge AI models trained in controlled laboratory settings. Systems must be designed to operate reliably in unstructured, dynamic environments—such as outdoor tracks, gyms, or sports arenas—where occlusions, perspiration, and hardware misalignment are common. Robust data preprocessing, adaptive filtering, and sensor fusion techniques (e.g., combining IMU + vision + EMG) improve performance under such conditions (Babu, Thuau, & Mandal, 2023). Additionally, self-calibration and context-aware models are being explored to automatically adapt AI behaviour to new users or surroundings.

Athlete-specific modelling and personalization

Wearable-AI systems also enable personalized modelling, where each athlete’s unique movement patterns, anatomical characteristics, and injury history are embedded into the system’s prediction and recommendation pipeline. Longitudinal data collected via wearables can be used to build individualized baselines and track deviations across training cycles. For instance, a smart insole might detect early changes in plantar pressure distribution indicative of overload, triggering a tailored intervention before injury onset. This aligns with the broader movement toward precision sports medicine, where interventions are dynamically adapted to the athlete’s state and context (Seçkin, Ateş, & Seçkin, 2023).

Data infrastructure, privacy, and deployment challenges

Despite technological readiness, large-scale adoption of AI-wearable systems still faces data governance and operational challenges. Reliable performance requires secure pipelines for data acquisition, annotation,

storage, and transmission, as well as mechanisms for privacy protection and ethical compliance. Deployment across teams and institutions introduces issues of interoperability, battery efficiency, and cost scalability. Moreover, acceptance by coaches, clinicians, and athletes is contingent on usability, transparency, and demonstrable value in improving performance or reducing injury burden (A. Li & Huang, 2024). Future work must emphasize user-centred design and clinically validated outcomes to facilitate trust and uptake.

By uniting advanced wearable sensors, on-device AI inference, context-aware adaptation, and secure, personalized modelling, next-generation platforms overcome traditional laboratory constraints and deliver continuous, actionable insights directly in the field. Figure 4 summarizes this end-to-end system: raw data from IMUs, sEMG arrays, pressure insoles, and smart textiles are processed on edge devices (e.g., smartphones, AI accelerators) for low-latency feedback, while environmental adaptation modules ensure robustness under changing conditions. Concurrently, cloud-backed, privacy-preserving pipelines refine athlete-specific baselines for risk prediction and rehabilitation progress, closing the loop with real-time, multimodal cues that guide training adjustments and recovery interventions on the pitch, court, or track.

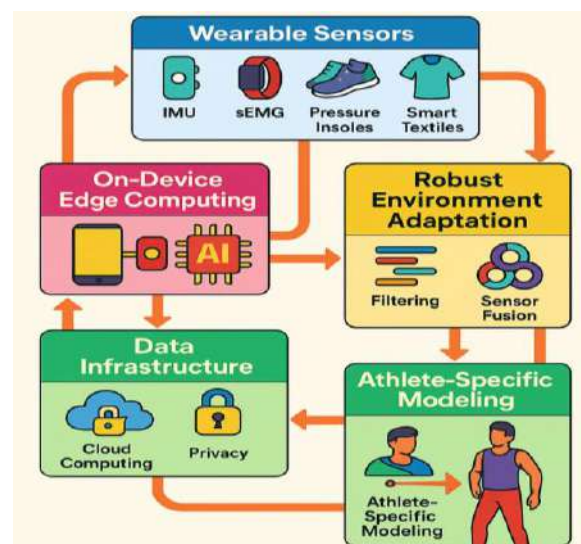


Figure 4. Integration of AI and wearables for real-world sports deployment.

Wearable sensors—including IMUs, sEMG arrays, pressure-sensing insoles, and smart textiles—continuously stream biomechanical and physiological data to on-device edge computing platforms (e.g., smartphones, dedicated AI chips). Robust environmental adaptation modules apply adaptive filtering and multi-sensor fusion to ensure reliable performance across variable lighting, surfaces, and user postures. Athlete-specific modelling components leverage secure cloud infrastructures and privacy-preserving techniques to establish personalized baselines for risk prediction and rehabilitation guidance. Continuous feedback loops deliver real-time, context-aware insights—via visual, auditory, or haptic cues—directly to athletes and coaches in training and field settings, enabling proactive injury management and tailored recovery interventions.

CONCLUSION

Artificial intelligence (AI) is transforming the landscape of sports injury prevention and rehabilitation by introducing intelligent, data-driven solutions that surpass the limitations of traditional assessment and intervention methods. By integrating multimodal sensor data, advanced machine learning algorithms, and

real-time processing capabilities, AI-enabled systems offer unprecedented opportunities for early injury risk detection, precise rehabilitation monitoring, and personalized feedback across diverse athletic populations.

This review has provided a comprehensive synthesis of recent advances across the AI-injury management pipeline. In injury risk prediction, machine learning models have demonstrated the ability to identify subtle biomechanical and physiological precursors to injury, especially when trained on high-quality, longitudinal datasets. In the rehabilitation domain, AI-supported systems are enhancing motion quality analysis, delivering real-time feedback, and adapting interventions dynamically based on user-specific recovery trajectories. Furthermore, the integration of wearable technologies and edge computing infrastructures has enabled the deployment of AI systems outside controlled laboratory environments, bringing intelligent feedback directly into training fields, clinics, and homes.

Despite these advances, challenges remain. Model generalization, interpretability, data privacy, and clinical acceptance continue to limit widespread adoption. Many systems still lack standardization in data collection, validation protocols, and usability design. Additionally, the absence of large-scale, domain-specific benchmark datasets hinders the fair evaluation and comparison of emerging methods. Addressing these challenges will require interdisciplinary collaboration among AI researchers, sports scientists, clinicians, and hardware developers.

Looking forward, the field is poised to shift toward personalized, explainable, and context-aware AI systems that adapt to individual athlete profiles and environmental conditions. The integration of digital twin frameworks, multi-agent behaviour modelling, and multi-modal interfaces promises to expand the functional scope of AI in sports medicine. With continued progress in sensor technology, learning algorithms, and ethical governance, AI is expected to become a core enabler of injury-resilient training, optimized performance, and long-term athlete health.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication. P.W wrote the entire manuscript, S.W reviewed the manuscript and made corrections, and P.W and A.W processed the tables and figures.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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Anticipatory information sources in elite softball batting: A qualitative approach

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ABSTRACT

Batting performance against high-speed pitches in softball requires effective anticipation skills. While these skills can vary individually, it remains unclear which anticipatory cues players rely on. The aim is to explore the anticipatory information sources and pitch-related cues perceived and considered by elite softball batters. We interviewed eight elite softball players (25 to 50 minutes each), and their responses were transcribed and analysed using an open-coding approach. Subsequently, the responses were thematically organized into higher and lower-order themes. Seven higher-order themes emerged: consciousness, contextual information sources, kinematic information sources, tactical awareness, mentality/confidence, batting technique and strategy, and skill acquisition/training. These themes highlight the various anticipatory information sources players use, as well as the role of kinematic and contextual cues in batting performance. Further analysis revealed detailed lower-order themes within each higher-order theme. A temporal model was developed to illustrate the sequence and interaction of both kinematic and contextual information sources that influence the anticipation skills of expert softball players.

Keywords: Performance analysis, Decision-making, Game performance, Kinematics, Perceptual training, Anticipation, Visual perception.

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INTRODUCTION

Anticipatory skills during hitting play a crucial role in softball. Like other sports, softball is fast game, constantly evolving, and its players are reaching higher levels of individual skills. Hitting is essential for success, and players are continuously pushed to improve due to the high quality of pitchers. The pitching speed imposes limitations on information processing and motor responses. Nevertheless, the best batters are able to consistently hit the ball even against the top pitchers, successfully reaching first base approximately once every three at-bats. Players individually utilize specific advance information, which may influence their behaviour at the plate or their efforts to analyse and successfully hit the upcoming pitch.

Anticipation research often employs partial video occlusions followed by the athlete's response (Williams et al., 2011). These studies typically focus on kinematic information sources for anticipation, such as the opponent's movements or the ball flight (Morris-Binelli et al., 2020; Shim et al., 2006). Müller et al. (2017) investigated the ability of expert and nearly-expert baseball batters to predict the pitch type from six different pitch types and the resulting pitch location—inside or outside—based on video recordings of pitchers. The results showed that the anticipatory skills of professional and semi-professional baseball players did not significantly differ. Their findings indicate that players struggle to anticipate both the type and location of the pitch simultaneously; however, they are significantly more successful when anticipating either the pitch location or type independently.

Previous research consistently shows that expert players outperform beginners in anticipation skills (Abernethy & Russell, 1987; Shim et al., 2005), and that expert players utilize different informational cues (Müller et al., 2009) and employ different visual search strategies (Mann et al., 2019; Murray et al., 2017; Sáenz-Moncaleano et al., 2018). Moore & Müller (2014) demonstrated that expert baseball players are consistently able to use and transfer visual information to anticipate subsequent events. In another study (Müller & Fadde, 2016), it was found that players can distinguish a change-up from a fastball during the pitch release occlusion, suggesting that visual anticipation based on prior information is a key component of batting performance.

Other studies have found that players use not only kinematic information for anticipation but also contextual information such as the match score, weather conditions, and the opponent's position (Vernon et al., 2018). For example, in tennis, during “*big points*” (e.g., break point), the receiving player often anticipates that their opponent will serve their favourite serve type. These contextual factors influence players' anticipation, highlighting the importance of considering players' approach from a broader perspective, rather than focusing solely on kinematic information.

Recently, there has been growing scientific interest in qualitative studies on anticipation research (Carboch et al., 2023; Vernon et al., 2018). These studies offer new perspectives and valuable insights into players' approaches and behaviours. While research on anticipation exists in various sports games (Abernethy & Zawi, 2007; Gabbett et al., 2007; Hopwood et al., 2011; Müller et al., 2006; Williams et al., 2003), including the aforementioned qualitative studies, to the authors' knowledge, no such research has been conducted in softball. Consequently, it remains unclear what cues, information, and approaches players use to anticipate pitches and enhance their batting performance. The aim is to explore the anticipatory information sources and pitch-related cues perceived and considered by elite softball batters.

MATERIALS AND METHODS

Participants

Eight (8) softball players participated in our study. All players (age $25,5 \pm 3,5$ years) were members of the Czech men's national team with experience in softball ($18,7 \pm 6,4$ years of experience). All players have experience from many international tournaments, including European and World softball championships, where they faced the best pitchers in the world. In addition, they have achieved above-average batting statistics in the highest national league for several years. The sample size of expert softball players adequately reflects level of expertise (Müller et al., 2015; Vernon et al., 2018). The study was approved by the Ethics Committee at the Faculty of Physical Education and Sport, Charles University, in accordance with the Declaration of Helsinki.

Procedure

The participants were approached and asked if they would agree to participate in the semi-structured interview that ranged from 25 to 50 minutes, where they considered in detail the key factors anticipating a softball pitch during their careers. A calm place and time without any distractions was arranged to complete the semi-structured interview. Before the interview, each participant reviewed the purpose of the study and provided informed consent. The interviews were recorded on the digital voice recorder application contained in the iPhone XS. Interviews were then transcribed verbatim to be used for analysis.

We used an interview guide and methodology previously developed for tennis research (Vernon et al., 2018), modifying it to suit the context of softball with the help of one expert coach, two elite players and one researcher. The core of the interview guide (relatively unstructured) consisted of the same open questions, aimed at eliciting comprehensive responses from each participant and asking follow-up questions. This approach, characterised by its flexibility, facilitated the exploration of participant responses through probes and follow-up inquiries, thus ensuring a thorough in-depth understanding of their answers and perspectives (Hardy et al., 2017). Table 1 presents the interview guide with the questions. All participants answered the questions based on their own personal experiences with complete freedom in their responses, including the deepest details of the topic discussed.

Table 1. Interview guide for participant interview questions.

-
1. Can you think of examples of past or present players who are/were good pitchers (hard to hit) and why?
 2. When you are going in the batting box, did you consider contextual information to help predict an opponent's pitch? (e.g., match status, number of runners on base, number of outs, spectators, importance of the game, weather, left-handed/right-handed pitcher, etc.)?
 3. What role did kinematic information (e.g., pitcher arm movements, refusal gestures, glove position, etc.) play in helping you anticipate or predict the pitch? Was it more important than the contextual information? Why?
Do you try to time your swing to the pitcher if you are in batting circle?
Do you discuss with your teammates about the next pitch type/location?
 4. If you utilized such contextual information how did you update it over the course of a match? For example, how many times did a pitcher have to throw the first pitch to the same location or when the same pitch type when you had two strikes count before you considered this a trend and adjusted your response accordingly?
Do you adjust the size of the strike zone according to individual umpires during a game or a batting start?
 5. Do you prepare for a match if you know that you will be facing a specific pitcher, what is his dominant pitch/location, batting practice, etc.? Do you watch an unknown pitcher on the video before the match?
 6. Based on your experience, what precedes a good hit? In other words, what key factor usually happens before you hit a hard hit? For example, gauging the pitch type, location outside/inside, swing timing, watching the ball at bat (head lock), etc.
 7. Do you try to anticipate the next pitch, or do you focus only on the pitch during the ball flight and strive for the maximum level of concentration, to have a so-called empty head, and why?
 8. Anything else you would like to add about the pitching and batting and what we have covered today?
-

Data analysis

Following the methodology outlined by Vernon et al. (2018), we used the open-coding analysis approach (Hendl, 2005; Straus and Corbin, 1998). Three experienced evaluators with research and practical understanding of slang and the specific language performed the analysis. The transcribed interviews were individually coded sentence by sentence by the evaluators separately to draw upon the emerging themes from the participants' responses to the interview questions. During the coding process, the interview sentences were given tags related to the codes that emerged. Based on the tags from each researcher, common themes were included and categorised into higher or lower-order themes. In case of differing themes between the researchers, the findings were discussed until a consensus was reached. For further details regarding the analysis, see Vernon et al. (2018).

RESULTS

A thematic analysis produced seven higher-order themes, which were extracted from the respondents' answers that had previously been identified. They are summed up in the themes and labels below (based on the language of the participants rather than the scientific language). Table 2 shows and summarises each of the themes. A model depicting the use of anticipatory information during softball batting is presented in Figure 1 at the end of this section.

Table 2. Summary of higher-order themes and their corresponding lower-order themes emerging from the batting anticipation interviews.

Higher order themes	Lower order themes
Consciousness	Anticipation: Being aware of contextual and kinematic informational sources. See the ball early off the hand. Pre-game anticipatory sources: Gathering information about the opponent through discussions with teammates and coaches before the game, as well as reviewing video footage of the opponent prior to the game. Anticipation training: Utilizing anticipatory sources.
Tactical awareness	Searching and updating information sources: batter searches for sources during the match, attempting to use them for his own benefit or for the benefit of his team. Evaluating current game situations. Tactics in the box: Adapting or changing tactics in the box based on kinematic and contextual information based on the current game situation. Conscious evaluation of anticipatory sources: Selecting or guessing.
Contextual information sources	Weather: Pitch quality and accuracy. Game situation: Score, runners on bases, outs. Observing trends: The attempt to observe a recurring trend by analysing previous starts in the match. Catcher's sequence: Observing the repeating sequence of the catcher in pitch selection. Signals from teammates: from the second base runner or a next batter in batting circle. Pitch count. Adjusting the strike zone according to individual umpires.
Kinematic information sources	Utilizing kinematic anticipatory sources. Pitcher's movements before the pitch: Body movements, forearm muscles, adjusting the ball in the glove, depth and angle of the pitching hand's insertion in the glove. Ball flight trajectory.
Mentality / confidence	Confidence in batting skills: As the pitch speed increases, the level of anticipation for the next pitch also increases. Pitch count: Balls/strikes.
Batting technique and strategy	Pitch selection: specific pitch type the batter wants to hit. The relationship between pitch speed and setting the batter's strategy for the game. Parameters of a hard hit: The skill of timing the swing.
Skill acquisition / training	Gaining experience by playing matches. Early age anticipation sources training and awareness: Pitching machine/pitcher.

Consciousness

All participants mentioned that they are aware of several sources of anticipation that they take into account before the match itself and then before every pitch. Before the match itself, the players have several information sources at their disposal, according to which they can set their pre-match strategy and create a plan in their head with which they enter the match. This plan can then change depending on other information sources, such as contextual information sources depending on specific situations, kinematic information sources about the opponent, or information obtained from teammates during the match. Being aware of kinematic information sources, two participants stated that they cannot use kinematic information about the opponent, despite the fact that they consider this information to be very important from the point of view of the success of the batting start. Participant 4 does not use this information purposefully. In contrast, however, all eight batters use pregame anticipatory information about the opponent, such as the pitcher's dominant pitch, frequency of different types of pitch in previous games, and so on. It is also important for the batter to anticipate the type of pitches and whether the batter is right-handed or left-handed, as a right-handed pitcher is unlikely to throw a curve/screwball to a batter standing in the right box. The responses indicate that batters adjust their batting practice depending on which pitcher they will face in the next game, debate with their teammates about what pitches a pitcher is throwing in specific situations, visualise their previous starts against a particular pitcher, and prepare a strategy into the game, such as which pitch they want to primarily hit or what pitches the pitcher might throw them. According to participant 2, there is also a difference between preparing for matches in the Czech league, where he knows all the pitchers, and preparing for foreign pitchers: *"There is also scouting in the national team, where we watch the pitchers on video and try to notice how they throw each type of pitch and what his movement looks like. In America, we have a debate with other teammates who know the pitchers and decide what types of pitch could come to whom and under what conditions. Alternatively, what is the dominant pitch for the pitchers, and which one is worth waiting for before hitting."*

Tactical awareness

All participants confirmed that they evaluate several different sources of information during their start and adjust their tactics in the box to changing game situations such as the number and placement of runners on bases, the number of outs, and the state of the game. If there is a need to get a runner home from third base, players are willing to hit into a forced out at the cost of scoring a run for the team or swing with more control as mentions participant 6. According to proband number six, tactics also change according to the current situation in the field: *"If I have a runner on third base, or if we are down by one point in the end of inning, things change a little at bat, depending on the number of outs, for example. Then, for example, I try to play more confidently, to get the ball into play as it was."* Or participant 2: *"If there are no runners on the bases, I mainly manage the start of the at-bat according to myself so that I feel comfortable in the box, and I go calmly sharply even to the third strike, even though I may be strike out. When someone (runner) is on the base or there is an important match, I try to swing more but not to be strike out. So, I swing with more control."* On the contrary, two participants said that if their team is leading or losing significantly, then they aim for a homerun or a long hard hit to gain personal benefit.

Players are also constantly evaluating several information sources at the same time, and therefore often make decisions about which information source to prioritise, as there are situations when they have multiple information sources at their disposal, and there may be situations where anticipatory sources are mutually exclusive. All participants also choose the degree of reliability and the degree of risk, how much percent they will trust a certain source, and how much they will adjust the tactics in the box based on it. Participant 8 said that if he spots a repeated pitch in a certain situation three times in a row, he has that variation *"in his head"* but does not rely on it 100%. As a pitcher's velocity increases, so does his degree of reliance on a specific

anticipatory source. Participant 1 also works with several anticipatory sources at the same time, and if, for example, the runner from the second base signals him a pitch tip, he takes this information into account but also does not rely on it 100%. He adds that he still must stay as focused as possible, because even if a teammate tips the rise ball correctly, he has to figure out during the flight of the ball how high the rise ball is flying and whether he will try to hit it or not. So, he takes this information as good advice, but as a result he always relies primarily on himself and his batting skills. In his opinion, the correct evaluation of anticipatory information is difficult for younger players who do not have so much experience, as they cannot react in time and effectively if the following event does not correspond to the prediction. According to participant 4, it is necessary to start with the targeted evaluation of (anticipatory) information already in childhood: *"It is something that you have to learn, because you are concentrating on two things at once and chaos can arise in the framework of the division of concentration - what does it show me? Yeah, the rise ball outside... what should I do? And the pitcher is already pitching. So, if it starts from learning from young age, it is great, but it can cause problems for someone if they start later."*

Contextual information sources

The pitch count (ball/strike) is a contextual source reported by all participants. Participant 6 said that if a pitcher is in an unfavourable pitch count, he expects him to improve it with his favourite pitch *'...when he has 3 balls and 1 strike, I expect the fastball, for example.'* This batter also stated that if he hits a hard pitch in a game, he does not get that pitch for the rest of the game again, or only a limited amount, so he primarily focusses on and expects other pitch types in his next bat starts. Batters also look for contextual trends in the game, such as whether a pitcher starts every batter with a strike or a certain type of pitch. By analysing his previous batting starts and the starts of his teammates, he tries to spot some applicable trend, while the minimum number of repetitions of a certain situation to determine the trend is individual. If batters notice a recurring situation, they can adapt their box tactics to this trend. Most participants mentioned trying to decipher the catcher's sequences/algorithm of signals to the pitcher and predict the next pitch. Three of the batters said they try to guess the next pitches based on the catcher's sequences. Participant 8 usually tries to guess pitches based on the catcher's sequence and how well the particular catcher knows him. The participant tries to guess the pitch type if he feels that the catcher is showing the same signals as to previous batters. But if he feels that the catcher has changed the sequence, he does not try anything and is ready for anything.

Players also adapt their tactics in the box according to specific referees. Five of the eight batters confirmed that they change the size of the strike zone according to the particular umpire. If it rains during a game, players are cautious and watch to see if the pitcher's control over pitch placement is impaired by wetness or humidity. Participants can rely on signals from the runner at second base, who can see the catcher's signals and also has a better view of the pitcher's glove (to see the ball grip). All participants use these signal possibilities in their teams for specific pitch types or location in their teams to gain additional information about the next pitch. Batters are provided information about catcher position change from of the dugout or teammates.

Kinematic information sources

The movements of the pitcher, which the batter either consciously or unconsciously associates with specific types of pitches and then anticipates the following type of pitch based on them. All participants agree that this type of information is very valuable and that this skill is associated with a hitter's success. The use of this skill is counterproductive for three of the participants, as they have to split their attention on multiple factors, and the resulting batting performance is then worse than if they had only focused on their performance, and therefore one proband does not attempt to obtain this information at all. However, five participants say that

they use this skill to their advantage. The entire team, including coaches and scouts, participates in obtaining this type of information by specifically watching the pitcher during pitching in previous games, or by analysing video footage. If a batter can successfully predict the types of pitches from the forward movements of the pitcher, it is a vital weapon that can significantly help the batter hit successfully. The participants mentioned specific cues: the angle and depth of immersion of the pitching hand in the glove and the movements of the forearm that accompany setting the ball in the correct position in the glove. Two participants mentioned, that they could recognize the pitch type from the forearm muscles, however the pitchers wear a long sleeves now to hide this cue.

Gathering pitcher kinematic information is primarily obtained by watching the pitcher from the dugout, from the stands, or by watching and analysing video footage. They (players and coaches) are looking for a specific movement that is connected to the subsequent action. This information is shared within the team. Participants number six states that the batter's box is the place where the application of the acquired kinematic information already takes place: *"The batter must already have information about the pitcher's movement before the pitch when he goes to the box. You already have to know what it does and then apply it in that box or try to apply it. The moment you don't see what you saw from the dugout, or what someone else tells you, then you need to get rid of it."*

The answers show that some batters can read the swing pitch from the pitcher's kinematics during the pitch, when the pitcher swings his torso to the side from the straightforward direction of the pitch. Some batters can recognize a change up when the pitcher slows down his movement before releasing the ball. The answers also show that the more starts a batter has against a particular pitcher, the easier it is for him to anticipate from kinematic information, because he knows the pitcher's movement, knows what to focus on and subconsciously knows whether the pitcher is slowing down the movement or will throw a technical pitch, whether it's a screw, curve, drop or a rise ball. Participant 5 said: *"I am using my catcher experience. I am often catching to best Czech pitchers, I'm able to recognize the change up from the movement when we hit. When they start the movement, I subconsciously see what they are going to throw, because I have seen the movement so many times that I can recognize it and react to it."* This information is supported by participant 3: *"I perceive the pitcher subconsciously, if I have watched (studied) a specific pitcher many times, then I know that he will throw a screw/curveball."* Participant 6 claims that the evaluation of information in this phase of the movement occurs automatically without the batter's voluntary effort: *"I do not purposefully follow the kinematics of the pitcher during the movement. I can kind of subconsciously know if the pitcher does something different, like slows down the change up or leans to the side at the point, the body reacts to that, but it's not something I have to focus on."*

Mentality/confidence

All participants revealed they never rely on information sources about the next pitch on 100%, and the final decision on whether to swing or not to swing depends on evaluating the pitch characteristics (spin, speed, direction). Even if the batter has advanced information about the type of the next pitch, i.e. its spin or location (height, inside/outside) before the ball release, he must consider the pitch variability since the pitcher is not a machine and every pitch is unique. However, as most participants said, in most cases, batters have incomplete, minimal or no information. The batter must primarily rely on his batting skills, and that is why self-confidence and mental toughness are essential, especially in critical moments of the match, when it is necessary to move runners on the bases by batting. Participant 1 said that if he has a form, he does not take contextual information into account or change anything in the box; however, if his form stagnates, he returns to controlled batting at important moments. In the batting box, batters try to be as concentrated as possible and not succumb to pressure from the environment, such as pressure to perform or the presence of

spectators. One participant admitted that many spectators' presence negatively affects his batting performance, as he tends to be nervous. Another participant said that the large number of spectators affects him emotionally, but he cannot specify whether it is positive or negative. Batters can also be nervous when they are expected to bat or when it is a crucial match moment. Participant 7 stated: *"I take it as a huge drag on my performance, thinking that I must send home three runners now because we have to win. However, I know that I could not remember what I was thinking of (solving) if I had a strong or important hit. Suddenly, it was such a flow when I did not solve anything, and it went on its own."*

Some batters try to the pitcher under pressure. For example, if pitchers have three balls without a strike, they make it clear that they will not hit the next pitch, for example, by indicating a bunt. Participant 2 said: *"I will signal a bunt to the pitcher, and no matter what pitch type he throws, I will not attempt to hit it"*. Another participant mentioned that if a pitcher refuses catcher's signals (for a pitch type), he takes time (time-out) to make the pitcher uncomfortable.

Batting technique and strategy

All eight participants agree that going into the batting box with a strategy against high-quality pitchers is important. Batters decide in advance which pitch type they want to hit and do not attempt to hit other pitches. For example, one of the batters always tries to hit a change-up if he knows the pitcher will throw it. Participant 1 concentrates on the dominant pitch: *"If the pitcher throws drop ball in 80% of the pitches, I only try to hit drop balls, nothing else"*.

Most participants agreed that the faster the pitcher's velocity is, the more they stick to the batting strategy, and improvisation disappears. On the other hand, with decreasing pitch velocity, batters enter the box with an empty head, as the time that elapses between the release of the ball by the pitcher and the contact of the ball with the bat is enough for them to recognize the pitch speed, type and location in time. If the pitch's high velocity does not allow this option, batters split the strike zone into two halves and only swing pitches that fly to that one half or attempt to hit only one pitch type. Participant 8 revealed: *"It depends on how fast the pitcher is and how pleasant he is to me. It is actually about my feeling. Sometimes I do it this way, and sometimes I do it that way. I have not set it beforehand, but the pitch speed is probably the most important factor. If I cannot keep up, I tell myself something and act accordingly."*

Five participants see the swing timing as a key factor in hard hits. Seven participants try to get the timing right in the warm-up circle, where they perform practice swings. Other factors used by batters as key to hitting hard were evaluating the type or location of the pitch. If a player can only perceive and use a minimum of context or kinematic information sources during a match, he must rely on his batting strategy based on pre-match scouting and setting his plan. Participant 5 stated on the batting strategy: *"It occurs to me that after a certain level in softball, the see the ball, hit the ball rule does not apply. Yeah, it just does not work (for the minor leagues, it works, but definitely not for the international level). Then I have to go into the batting box with a plan and think about what they are pitching, for sure, and you cannot make any progress without that in world softball, how fast the pitchers throw."*

Skill acquisition/training

Three participants mentioned that the younger generation of batters, who practice perceiving and evaluating anticipatory sources from a young age in junior categories, are more successful in this anticipation/batting area. Participant 4 comments regarding the pitcher's kinematic information: *"I think this skill can be learned like other techniques in hitting. For example, Bred Rona from New Zealand claimed that before the pitch is*

released, he knows in 90% of cases what the incoming pitch will be. Either he reads it from the box, or someone from his teammates advises him, but mostly he reads it from the box".

Most participants agreed that the swing timing skill can be practised by facing pitches. Facing a pitching machine has the disadvantage that the machine is always pitching velocity, and the batter does not have to adjust the swing timing for each pitch. Batting in the cage from the front toss has the advantage that pitches can be easily placed on any part of the strike zone, and hundreds of balls can be pitched this way without higher demands on the pitcher's condition or technical equipment. However, pitches made with this style are relatively slow. In the batting cage practice, it is impossible to achieve sufficient development of this batting skill (timing) since the distance at which the ball is pitched, and the speed of the pitch do not imitate match conditions. Three participants agreed that match experience and training with live starts are most valuable for a batter. According to participant 3, players who play all year-round, without a winter break, such as Latin American nations, have the greatest advantage while having the opportunity to gain more experience from real match starts against pitchers, as well as players who regularly bat against fast pitchers. Participant 1 stated, "You definitely cannot be a top batter based only on (batting) cage practice. The key element is to see live pitches regularly, even in practice."

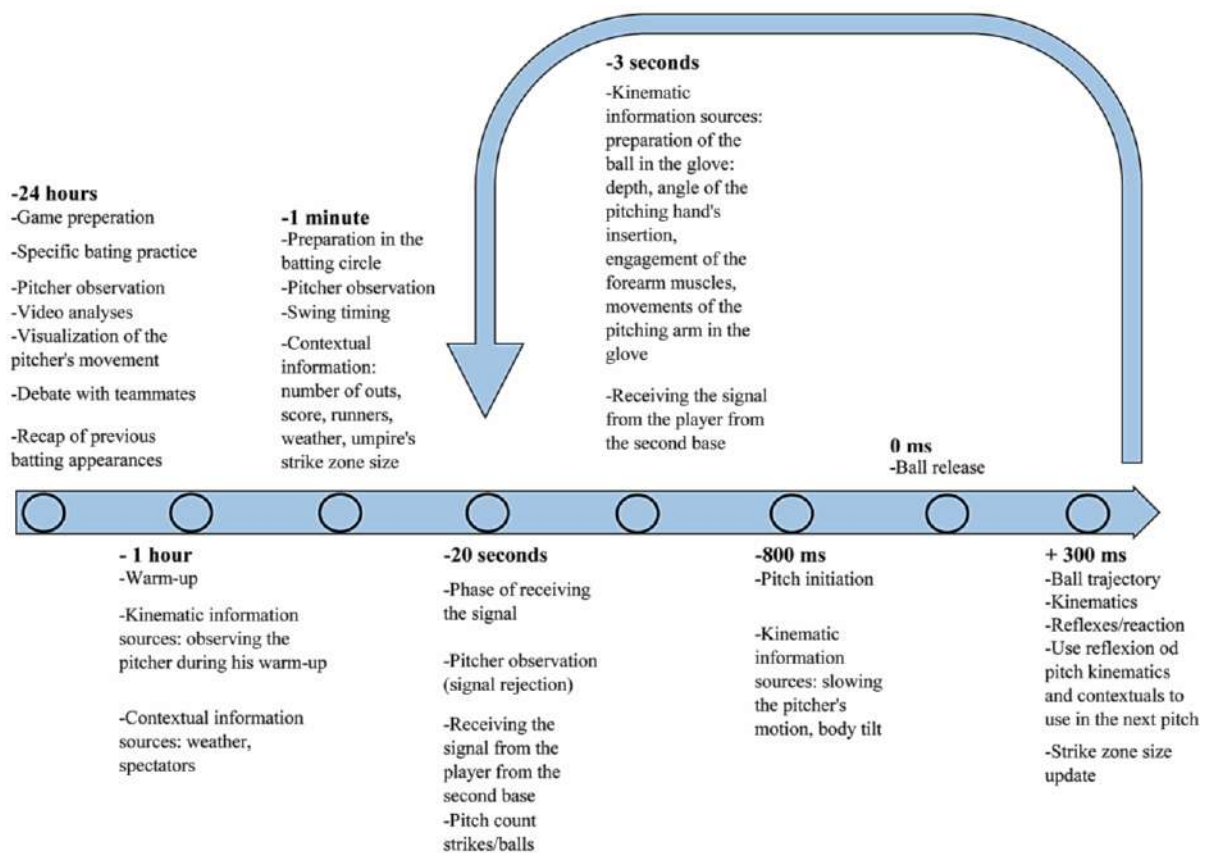


Figure 1. Temporal model illustrating how anticipatory information is utilized during softball batting.

DISCUSSION

The interviews revealed several common ideas, players' approaches, and hitting strategies that were agreed upon by several or most of the interviewed batters, independently of each other. However, some of

the insights shared were unique and original, highlighting the ambition and effort of batters to read the opponent pitcher and predict their intentions. Some batters went further in their reasoning than others. However, all participants anticipate and sometimes rely on advance information to predict the next pitch.

Batters use various anticipatory sources to anticipate pitches. Typically, they start by preparing for the game based on the pitcher they will face, often through pre-game scouting, which includes direct observation or video analysis. Once they have this information, batters prepare during batting practice for the types of pitches they expect to see in the upcoming game, or they visualize the pitcher's pitches. Familiarity with a pitcher's video footage helps batters understand their movements and identify the types of pitches the pitcher uses, similar to how a tennis player anticipates an opponent's favourite serves during critical points (Vernon et al., 2018). In tennis, players face many serves and update their information based on the opponent's movements. This helps them predict the type of serve after observing 10 to 30 serves, which could make up a third of the match. In softball, however, each batter faces only a few pitches per game, meaning there's less opportunity to update kinematic information from personal experience, but each batting start helps.

The responses revealed that the use of anticipation increases with the speed of the pitches. The faster the pitches, the harder it is to react solely based on visual information about the ball's trajectory, prompting batters to predict the type or location of the pitch. To do this, they rely on visual or contextual anticipatory cues, as well as information from pre-game scouting. However, most participants agreed that the better the pitcher, the more difficult it becomes to observe anything in the pitcher's kinematics—either before or during the pitch—that could help the batter anticipate the upcoming pitch. As a result, this informational resource becomes less useful when facing top pitchers, and batters (according to the responses) might divide the strike zone into two halves or attempt to hit only one type of pitch. In such cases, anticipation turns into more of a guessing game.

For a successful hit, the key factor is the proper timing of the swing, which means the point where the bat's flight phase intersects with the ball's flight phase (Katsumata, 2007). According to Joska (2019), batters are able to time their swing relative to the changing speed of the different phases of the swing and the varying time allocations for each phase. From a training perspective, it is essential to simulate the timing requirements of a real game. This means the training must match both the game's pitching distance and the pitch speed. This can only be achieved with live pitching or by using a pitching machine. However, when hitting off a pitching machine, the length of the stride and swing tend to increase (Aubrecht, 2017; Carboch et al., 2022). Therefore, the best training for batting skills—specifically timing—consists of simulated batting starts during practice or actual game situations.

The interviews indicate that all the participants consider kinematic informational sources from the pitcher both in and outside the batter's box. For a batter to use these advance information directly in the box, they must already know in advance what to look for in the pitcher's kinematics. This is why players or coaches observe the pitcher's movements before the game during warm-ups, as well as during the game from the dugout or batter's circle. Some participants, after the pitcher starts their motion, are unable to extract anything from their movements and focus solely on themselves. Meanwhile, other batters can detect shifts or slowing of the pitcher's movements and anticipate a technical pitch or change-up. This skill can correlate with how familiar the batter is with the specific pitcher and also highlights differences in anticipatory skills among high-level players.

The participants reported minimal exposure to targeted anticipation training, which suggests potential areas

for improvement in training for batting performance. Perceptual training (Brenton et al., 2019; Gabbett et al., 2007; Hopwood et al., 2011), which involves watching occluded video clips and predicting the next action, could be valuable for enhancing these skills. This approach could be recommended for coaching practice. Among the players who have the most opportunity to observe pitchers are catchers, which helps them better read the pitcher's movements. However, it was not confirmed that catchers are better batters than players in other positions (Klein, 2015). This may be because catchers, after pitchers, are the most physically active players, performing several squats and throws during each inning. As a result, they enter the batter's box more physically fatigued than players in other positions. Fatigue in the lower limbs can also cause slower sprints to first base, leading to lower success in batting statistics. Additionally, catchers must focus on every pitch, which can lead not only to physical fatigue but also mental fatigue, potentially reducing reaction times compared to players in other positions who are not as heavily involved during the game. In training, catchers often catch pitches for pitchers, which can limit their opportunities to practice hitting.

The interviewed batters reached a consensus regarding the adjustment of the strike zone size according to the individual umpire and the batter's situation. Specifically, five batters adjust the size of the strike zone based on who the home plate umpire is during the game. They are prepared to swing at pitches they personally wouldn't consider strikes but believe the umpire would call a strike. On the other hand, six participants expand the strike zone when they have two strikes. Interestingly, according to a study by Huang & Hsu (2020), professional baseball umpires tend to shrink the strike zone when there are two strikes, while they expand it when there are three balls.

One limitation of the research was the extensive responses from the players, which often strayed from the original question. While these off-topic responses provided interesting insights, sometimes players did not answer the questions in detail, which should be addressed in future research. Further studies should focus on surveying professional and semi-professional softball players from other countries.

CONCLUSION

Anticipation plays a crucial role in softball high-level hitting, and as the speed of the pitches increases, the level of anticipation rises. The anticipation informational sources batters consider include the pitcher's kinematics, information about the opponent (such as the pitcher's dominant pitch and preferred locations), analysis of previous matchups against the specific pitcher, and the catcher's sequence. However, the interviews revealed that batters do not always have access to these pieces of information due to the pitcher's unreadable movements. In these cases, guessing comes into play, where batters, for example, divide the strike zone into two halves and only swing at pitches in one of those halves. Players also adjust their strategy in the batter's box based on contextual information such as the number of outs, runners on base, or the presence of a particular umpire. Better performance in anticipation in batting box is facilitated by prior knowledge of the pitcher. According to the players, the greatest benefit for developing anticipatory skills comes from facing top pitchers in actual games, as such conditions are difficult to replicate in training. Therefore, for improved batting performance in softball, it is essential for as many players as possible to regularly participate in international tournaments where they can gain experience against foreign pitchers.

AUTHOR CONTRIBUTIONS

Jan Carboch and Petra Praveckova conceived and designed the investigation, analysed and interpreted the data, drafted the manuscript, and approved the final version submitted. Marek Joska collected and interpreted the data.

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Physical fitness among elite female football and handball players: A comparative analysis

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ABSTRACT

This study examined the differences in physical fitness between elite female football and handball players competing at the highest level. A total of 38 athletes participated, divided into two groups: football players (N = 20) and handball players (N = 18). Anthropometric characteristics, body composition, and motor abilities, including speed, agility, and explosive strength, were assessed using standardized tests. The results revealed significant differences in body composition, with handball players being taller (173.6 ± 4.7 cm vs. 165.7 ± 4.7 cm, $p = .00$) and heavier (69.7 ± 10.9 kg vs. 60.9 ± 8.0 kg, $p = .00$), while football players had a higher percentage of muscle mass ($42.9 \pm 3.4\%$ vs. $32.2 \pm 2.7\%$, $p = .00$) and lower body fat ($22.4 \pm 6.1\%$ vs. $27.6 \pm 6.0\%$, $p = .01$). Regarding physical performance, football players outperformed handball players in agility, particularly in the zig-zag test (5.74 ± 0.32 s vs. 6.08 ± 0.38 s, $p = .00$). Conversely, handball players demonstrated superior explosive strength, as evidenced by better results in the countermovement jump with arm swing (CMJa: 32.5 ± 5.0 cm vs. 28.8 ± 3.4 cm, $p = .01$). No significant differences were found in sprint performance over 10m (1.84 ± 0.16 s vs. 1.89 ± 0.12 s, $p = .25$), 20m (3.35 ± 0.22 s vs. 3.33 ± 0.18 s, $p = .78$), and 30m (4.66 ± 0.20 s vs. 4.75 ± 0.24 s, $p = .20$). These findings highlighted the influence of sport-specific demands on athletes' physical profiles and motor abilities. Understanding these differences could assist coaches in designing targeted training programs to optimize performance and address specific fitness needs. Future research should incorporate a larger sample size and explore additional physiological and biomechanical variables to further elucidate the distinctions between these two sports.

Keywords: Performance analysis, Anthropometric characteristics, Agility, Explosive strength, Body composition, Speed.

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INTRODUCTION

Over the past decade, female team sports have seen significant growth and received a lot of attention (Elliott-Sale, Minahan, de Jonge, Ackerman, & Hackney, 2021). Contemporary intermittent team sports demand a diverse set of physiological characteristics to be able to meet the requirements of the game (Dasa, Kristofersen, Ersvær, Bovim, & Haukenes, 2021). In team sports, the quickness and explosive force of game activities enhance via training and competition. Regarding that, experts in this area are exploring novel approaches to help athletes improve their physical and technical abilities (Bush, Barnes, Archer, Hogg, & Bradley, 2015).

Football is rapidly becoming the worldwide leading female sport (Read, Mehta, Rosenbloom, Jobson, & Okholm Kryger, 2022). Elite football players usually cover approximately 10 km throughout a single match, demonstrating a high level of activity. High-intensity running and sprinting account for 22-28% of the overall match distance and require additional metabolic and physiological resources, such as the anaerobic energy system (Ramos, Nakamura, Penna, Wilke, & Coimbra, 2019). The usual sprint interval is between 2 and 4 seconds and happens at key moments throughout a match, while nearly all sprints occur over distances shorter than 20 meters (Andrašić, Gušić, Stanković, Mačak, & Trajković, 2021).

On the other hand, handball success demands scoring more goals than the rival after two 30-minute halves. Analysing aspects of performance is crucial for achieving victory (García-Sánchez, Navarro, Mon-López, Nieto-Acevedo, & de la Rubia, 2024). Handball is a team sport that alternates between low-intensity motions and high-intensity actions, including constant and intense physical contact with rivals (Wagner, Fuchs, Fusco, Fuchs, & von Duvillard, 2019). Throughout various high-intensity occasions, players are required to execute a variety of basic movement patterns (directional changes, accelerations, decelerations, jumps, sprints) as well as handball-specific movements (hits, throws, blocks and pushes) (Iacono, Eliakim, & Meckel, 2015). Elite female handball players travelled approximately 4 kilometres in one competitive match. The overall distance completed throughout a match includes around 9.2% sprinting and 26.7% quick running, highlighting the sport's reliance on agility and speed (Papaevangelou, Papadopoulou, Michailidis, Mandroukas, & Metaxas, 2023).

When it comes to previous research, several studies have dealt with similar topics in female football and handball. In this regard, two studies, in both genders (Stankovic, Malacko, & Doder, 2009; Gusic, Popovic, Molnar, Masanovic, & Radakovic, 2017) reported differences in height, weight, and subcutaneous fat, where handball players had higher values compared to soccer players. Previous studies (Petruț-florin, Lepciuc, & Florentina-Petruța, 2021) demonstrated significant differences in body mass (kg) between female soccer (57.44 ± 9.12) and handball (70.03 ± 8.33). The same study also confirmed differences in explosive power of lower limbs in the countermovement jump (CMJ) (37.01 ± 4.29 vs. 39.21 ± 4.69), squat jump (SJ) (34.62 ± 3.66 vs. 37.69 ± 4.27) and free jump (FJ) (42.78 ± 5.31 vs. 44.14 ± 3.90) tests, as well as isometric strength (60.63 ± 10.84 vs. 70.43 ± 9.37) in favour of handball players. When we looked at speed and agility, it was reported that handball players from first division showed better results on the zig-zag test than soccer players same rank of competition (Freitas, Pereira, Alcaraz, Comyns, & Loturco, 2022). On the other hand, the same study confirmed that soccer players displayed inferior sprint momentum when compared with the other sports (handball, rugby).

Given the fact that there is a difference in the aforementioned variables between sports, as well as the specific requirements of the two previously mentioned team sports, it is very important to determine the differences in physical fitness between sports. Understanding these differences is crucial for developing sport-specific

training programs to optimize performance and fill existing gaps in research, as studies involving female athletes remain underrepresented in sports science. Previous studies have examined differences between female athletes in various sports, but only one has specifically compared female soccer and handball players. Most existing research has either included additional sports, such as rugby, or primarily focused on anthropometric characteristics and body composition. However, there is a lack of studies that provide a comprehensive analysis both body composition and various physical fitness qualities, such as strength, speed and agility in these two groups of athletes. Studies with female participants account for only 20% of total sport and exercise science research, indicating several knowledge gaps still exist on this topic in general (Stankovic, Djordjevic, Trajkovic, & Milanovic, 2023). Furthermore, the level of performance necessary to be identified as an elite athlete could differ over the years as sports improve and players grow stronger and quicker (Fitzgerald, & Jensen, 2020). Thus, the purpose of this study is to examine and investigate differences in physical fitness among female football and handball players in the highest rank of competition.

MATERIALS AND METHODS

Participants

The sample included 39 elite female athletes, consisting of football and handball players, all competing at the highest level of competition (Super League). However, it is important to note that one participant had to withdraw from the study due to an injury sustained prior to or during the research process. Players were divided into two groups: handball players ($N = 18$, age 20.22 ± 4.67 , body height 173.64 ± 4.71 , body mass 69.73 ± 10.85) and football players ($N = 20$, age 21.79 ± 3.77 , body height 165.70 ± 4.73 , body mass 60.92 ± 8.04). All participants were informed about the purpose as well as the risks and benefits of the research. Each participant gave their written agreement to participate in the testing after being informed about the details. The testing procedure and regulations were explained to participants, sports professionals, and club management. Additionally, the club's management gave their approval for the data collected during testing to be used for scientific research. Recruited players had at least 5 years of sport (football and handball) experience, a history of regular training (more than 4 times per week) in the previous 12 months, a weekly training schedule of more than 7 hours, and no medical conditions that would prevent them from participating. The protocol was approved by the Ethics Committee of the Faculty of Sport and Physical Education, University of Niš, Serbia (protocol code 04-1769/2, date of approval 18th of October 2024).

Procedures

Measurements of the physical performance and anthropometric characteristics of participants were conducted in a multidisciplinary diagnostic centre, as well as in the club premises and testing lasted one day for each sport. The time period for measuring the aforementioned variables in both cases was from 9 to 11 a.m. Testing was done by the same measurers on both days, at the same tests. All participants performed a standard warm-up protocol which lasted 20 minutes and included consisting of running (6 min), dynamic stretching (5 min), progressive running (3 min) and change of direction (3 min). After this protocol participants performed the following in order: anthropometric assessments, followed by physical performance tests, starting with vertical jumps (CMJ, CMJ with arm swing (CMJa), SJ), 30 m sprint with time recorded at 10 m and 20 m, t-test, Zig-Zag test and Illinois test.

Anthropometric assessment

Martin's anthropometer GPM 101 (GPM GmbH, Zurich, Switzerland) was used to assess body height with an accuracy of 0.1 cm. The subjects stood in an upright position, barefoot on a firm surface, with their feet together, the measurer made sure that the anthropometer was in a vertical position along the back of the

body and then lowered the sliding compass of the anthropometer to the top of the subject's head, the reading is made on the upper opening along the line that is the read indicator.

The following variables were collected after assessing body composition with the InBody instrument: body weight (BW), body mass index (BMI), body fat percentage (FM%) and muscle mass percentage (MM%). The InBody 770 instrument (InBody Co., Seoul, Republic of Korea) was utilized for the body composition assessments, and instrument validity has been demonstrated elsewhere (Gonzalez, Orlandi, Santos, & Barros, 2019). Furthermore, this approach has been used in research with adult elite athletes (Čoh, Vodičar, Žvan, Šimenko, & Mačkala, 2018; Stanković, Čaprić, Đorđević, Đorđević, & Sporiš, 2023).

Physical performance assessment

Speed (10m, 20m, 30m)

The speed assessment was performed using 10 m, 20 m, and 30 m sprint tests concordant to the described protocol (Zabalov et al., 2022). Photocells were used to estimate the speed for the 10, 20, and 30-meter sprint (Witty, Microgate, Italy). Participants repeated the speed test three times, and the fastest attempt was included in the statistical analyses. Photocells were placed at waist height, and the participants began the linear sprint. Test was performed by determining a 30-meter, players ran as fast as possible from the starting point to the last gate. Participants moved 1 m behind the first gate to prevent early gate activation. Testing was conducted after the intended warm-up. They had three attempts, the best result was taken for statistical analysis.

Agility Assessment (T-test, zig-zag and Illinois test)

Agility was assessed using Illinois, t-test, and zig-zag test. All tests were evaluated using a photocell system (Witty, System, Microgate, Bolzano, Italy).

In the t-test, three cones are placed in the same plane at a distance of 4.57 meters. The participant runs as fast as possible in a straight line from the gate to the first cone which is located in the middle at a distance of (9.14 m) and touches the top of the cone with his right hand, then with a lateral movement moves to the right cone (4.57 m from the middle cone), touches the cone with his right hand, touches the left cone with a lateral movement to the left, touches the middle cone again and then runs back to the starting position to pass through the gate. The reliability and validity were confirmed in a study (Pauole et al., 2000).

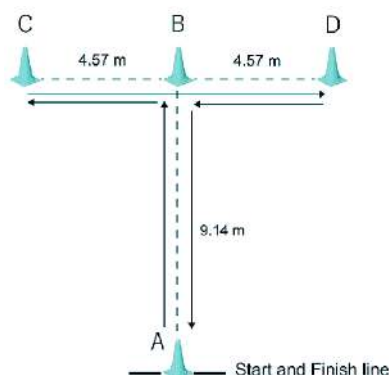


Figure 1. Agility T-test.

For the zig-zag test (ZZ) demands the examinee to complete what was planned in the shortest period of time. The test consists of four cones positioned at the corners of a rectangle (5 m x 4), with another cone put

in the centre of it. If the cones placed at the corners are marked 1 to 4, starting from the longer side, and the central one is marked C, the test starts at cone 1, and continues running around the cones to C, 2, 3, C, 4, and back to 1. The participants took a standing start position, with both legs behind the starting line. Six cones were positioned at a 2-meter distance, with the first cone 1m from the starting line. Each examinee stood facing the starting line, legs apart. Following the signal, participants ran from the first cone to the second, moving around it with their right side. After that, they kept running around the cones, going left and right, until they came to the final one. They pivoted and proceeded to slap their way to the finish or starting line. The reliability and validity were confirmed in a study (Kutlu, & Dogan, 2018).

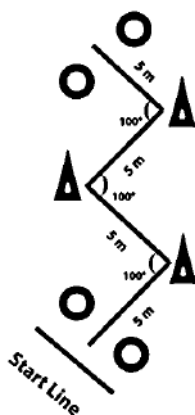


Figure 2. Zig-zag agility test.

Illinois agility test (IL), the participants start at the lower left cone, run in a straight line to the upper left cone, then go around it and return to the lower middle cone and begin slaloming, forming a figure eight. After leaving the figure eight, they run to the upper right cone, go around it, and finish the test at the lower right cone. The test is performed on a 10-meter-long and 5-meter-wide course, with four cones marking the start, finish, and turning points, and an additional four cones placed in the centre at 3.3-meter intervals to create the slalom section.

Participants were given three attempts to take each test, with two-minute rests in between. The rests between tests were three to five minutes. The reliability and validity were confirmed in a study (Hachana et al., 2013).

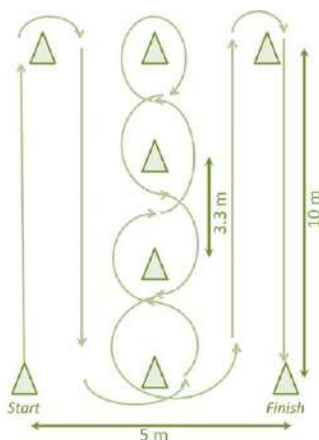


Figure 3. Illinois agility test.

The explosive strength of the lower extremities

Photoelectric cells (Optojump, Microgate, Bolzano, Italy) were used to assess the explosive strength of the lower extremities, the reliability and validity were confirmed in a study (Healy et al., 2016). The countermovement jump (CMJ) starts from a standing position with arms at the sides. Then, a flexion is performed in the knee joint without disturbing the previously mentioned position, and immediately after the extension in the knee joint, so that the body goes up and lands in the same place. The countermovement jump with arm swing (CMJa) is performed in the same way as the previously mentioned test but with the help of arm swing during the execution. Squat jump (SJ) starts from a squatting position with limited arm movement, hands are on the hips and then the subject jumps as high as possible. Each test is performed three times, with a rest between attempts were two minutes. These tests are valid and reliable to measure explosive power (Markovic et al., 2004).

Statistical analysis

Data analysis was conducted using the Statistical Package for the Social Sciences (SPSS), version 20.0 (SPSS Inc., Chicago, IL, USA). Descriptive statistics, including mean values, standard deviations, and 95% confidence intervals, were calculated for all measured variables. The Kolmogorov-Smirnov test was used to assess the normality of the data, confirming that all variables followed a normal distribution. To compare body composition and motor abilities between the handball (HB) and football (FB) groups, independent samples t-tests were performed. Statistical significance was set at $p < .05$. Results are presented as mean $\pm$ standard deviation (SD) with 95% confidence intervals (CI). Cohen's d effect size was calculated to determine the magnitude of differences between groups, with thresholds of 0.2, 0.5, and 0.8 indicating small, medium, and large effects, respectively.

RESULTS

Table 1 presents the mean values and standard deviations of body composition variables, including participants' age, body height, body mass, body mass index, body fat percentage, and muscle mass for the handball (HB) and football (FB) groups. The results of the Kolmogorov-Smirnov test indicate that all variables have a normal distribution. Also, Cohen's d effect size was computed to assess the magnitude of differences between the groups.

Table 1. Descriptive statistics and group comparison of body composition variables.

	HB (N = 18)	FB (N = 20)	K-S	p-value	Cohen's d
	Mean $\pm$ SD (95% CI)	Mean $\pm$ SD (95% CI)			
AGE	20.22 $\pm$ 4.67 (17.90-22.55)	21.79 $\pm$ 3.77 (20.70-22.88)	.851	.164	0.370
BH (cm)	173.64 $\pm$ 4.71 (171.29-175.98)	165.70 $\pm$ 4.73 (163.48-167.91)	.557	.000**	1.682
BM (kg)	69.73 $\pm$ 10.85 (64.34-75.13)	60.92 $\pm$ 8.04 (57.15-64.68)	.879	.000**	0.922
BMI (cm/kg ²)	23.04 $\pm$ 2.73 (21.68-24.40)	22.05 $\pm$ 2.57 (20.74-23.25)	.908	.266	0.373
%FM	27.62 $\pm$ 6.00 (24.63-30.60)	22.44 $\pm$ 6.14 (19.57-25.31)	.250	.013**	0.853
%MM	32.18 $\pm$ 2.70 (30.83-33.52)	42.96 $\pm$ 3.43 (41.36-44.56)	.265	.000**	3.492

Note. N-number of participants; K-S-Kolmogorov Smirnov test; BH-body height; BW-body weight; BMI-body mass index; %FM-percentage of body fat; %MM-percentage of muscle mass; $p < .05$; ** $p < .01$

Table 2 presents the mean values and standard deviations for motor abilities, in speed (10m, 20m, 30m), agility (TT, ZZ, IL), and jump tests (CMJ, CMJa, SJ) for the HB and FB groups. The Kolmogorov-Smirnov test confirmed that all data have a normal distribution. Additionally, Cohen's d effect size was calculated to determine the magnitude of differences between the groups.

Table 2. Descriptive statistics and group comparison of motor abilities.

	HB (N = 18)	FB (N = 20)	K-S	p-value	Cohen's d
	Mean $\pm$ SD (95% CI)	Mean $\pm$ SD (95% CI)			
10m (s)	1.89 $\pm$ 0.12 (1.83-1.95)	1.84 $\pm$ 0.16 (1.76-1.91)	.792	.254	0.353
20m (s)	3.33 $\pm$ 0.18 (3.24-3.42)	3.35 $\pm$ 0.22 (3.25-3.45)	.962	.778	0.099
30m (s)	4.75 $\pm$ 0.24 (4.63-4.87)	4.66 $\pm$ 0.20 (4.56-4.75)	.709	.201	0.407
TT (s)	10.69 $\pm$ 0.70 (10.34-11.04)	10.47 $\pm$ 0.38 (10.29-10.65)	.390	.233	0.390
ZZ (s)	6.08 $\pm$ 0.38 (5.89-6.26)	5.74 $\pm$ 0.32 (5.56-5.89)	.521	.000**	0.968
IL (s)	16.99 $\pm$ 0.52 (16.85-17.40)	16.90 $\pm$ 0.79 (16.53-17.27)	.772	.745	0.134
CMJ (cm)	27.41 $\pm$ 3.57 (25.63-29.18)	25.84 $\pm$ 2.66 (24.60-27.08)	.694	.136	0.499
CMJa (cm)	32.47 $\pm$ 4.97 (30.00-34.94)	28.80 $\pm$ 3.40 (27.21-30.39)	.389	.013*	0.862
SJ (cm)	25.07 $\pm$ 4.13 (23.02-27.13)	24.19 $\pm$ 2.77 (22.89-25.48)	.529	.448	0.250

Note. N-number of participants; K-S-Kolmogorov Smirnov test; 10m-10 meters speed test; 20m-20 meters speed test; 30m-30 meters speed test; TT-T test; ZZ-Zig zag test; IL-Illinois test; CMJ-Countermovement jump; CMJa-Countermovement Jump with arm swing; SJ-Squat Jump; BH-body height; BW-body weight; BMI-body mass index; %F-percentage of body fat; %M-percentage of muscle mass; $p < .05$; ** $p < .01$

The comparison between the HB and FB groups revealed significant differences in several body composition and motor abilities variables. The HB group had significantly greater body height (173.64 ± 4.71 vs. 165.70 ± 4.73 ; $p = .00$) and body mass (69.73 ± 10.85 kg vs. 60.92 ± 8.04 kg, $p = .00$). In terms of body composition, the HB group also exhibited a higher percentage of body fat (27.62 ± 6.00 vs. 22.44 ± 6.14 ; $p = .01$) and a lower percentage of muscle mass (32.18 ± 2.70 vs. 42.96 ± 3.43 ; $p = .00$) compared to the FB group. Regarding motor abilities, the HB group demonstrated significantly better results in the change of direction speed (ZZ test: 6.08 ± 0.38 s vs. 5.74 ± 0.32 ; $p = .00$) and the countermovement jump with arm swing (CMJa: 32.47 ± 4.97 cm vs. 28.80 ± 3.40 ; $p = .01$). However, no significant differences were observed between the two groups for the 10m, 20m, or 30m sprint times, agility tests (TT and IL), and other jump metrics such as the squat jump (SJ) and countermovement jump without arm swing (CMJ).

DISCUSSION

This research aimed to examine and investigate differences in physical fitness among female football and handball players in the highest rank of competition. The results of the conducted research indicated a significant difference in the parameters of body composition, primarily height, weight and fat percentage in favour of handball players, while the percentage of muscle mass was on the side of soccer players. Also, significant differences were found in individual tests, i.e. basic motor skills. The tests in which soccer players had statistically significantly better results was agility, that is, the zig-zag test, while handball players were better in explosive power, that is, the CMJ test.

The results of anthropometric measurements, height and weight, showed a significant difference in favour of the test subjects who practiced handball. These results are consistent with previous research (Milanese, Piscitelli, Lampis, & Zancanaro, 2012; Oyón, Franco, Rubio, & Valero, 2016). Which can be explained by highly selected athletes who are in accordance with the modern requirements of handball as a sports game, i.e. its specificities (Iacono, Eliakim, & Meckel, 2015). The specifics, first of all, of the longitudinal dimensions of the skeleton, must be as high as possible due to covering a large part of the field in defensive actions, but also in attack, where the largest number of shots directed at the opponent's goal end with high jumps in order to avoid blocking the opposing players and get into a more favourable position for a shot on goal (Gusic, Popovic, Molnar, Masanovic, & Radakovic, 2017). Also, differences in the percentage of muscle mass and fat were observed, where the percentage of muscle mass is significantly higher in soccer players, while the

percentage of fat is statistically higher in handball players. The results obtained in this way are in accordance with the authors' earlier research (Hewitt, Norton, & Lyons, 2014; Mala, Maly, Zahalka, Bunc, Kaplan, Jebavy, & Tuma, 2015; Papaevangelou, Papadopoulou, Michailidis, Mandroukas, Nikolaidis, Margaritelis, & Metaxas, 2023). Where the average height values for female handball players ranged from 167cm to 176 while for male soccer players it was 164-167cm, the body mass of female handball players was on average from 63.1 to 72.5 kg while for female soccer players it was from 58.7 to 61.3 kg. The average body fat percentage was around 26, while the average body fat percentage was around 20. The authors also explain such results by the nature of the sport, i.e. female soccer players have much greater physical efforts over a longer period of time because the match itself lasts much longer, the field is larger, as well as the weight of the props, i.e. the ball used to play (Hewitt, Norton, & Lyons, 2014; Mala, Maly, Zahalka, Bunc, Kaplan, Jebavy, & Tuma, 2015; Papaevangelou, Papadopoulou, Michailidis, Mandroukas, Nikolaidis, Margaritelis, & Metaxas, 2023).

The results in the basic motor areas that were analysed did not always indicate the same results, that is, out of the three motor areas that were analysed with nine tests (three for each), only in the speed tests there were no statistically significant differences. The results of earlier research that determined the speed of the tests applied to the sample of this paper also showed that no statistically significant difference was observed (Saavedra, Kristjánsdóttir, Einarsson, Guðmundsdóttir, Þorgeirsson, & Stefansson, 2018; Freitas, Pereira, Alcaraz, Comyns, Azevedo, & Loturco, 2022). The reason for the results obtained in this way can be found in statistical analysis during football and handball matches where there is no difference in the percentage of time spent running a distance of 20-30 meters (Andrašić, Gušić, Stanković, Macak, & Trajković, 2021). Earlier research highlights that the specifics of sports games in the field of basic motor skills often lead to no statistically significant differences in the initial stages of action development. However, differences become apparent in certain segments of motor performance, influenced by the length of actions and the spatial demands unique to each sport. These variations underscore the impact of sport-specific requirements on the physical abilities of athletes (Popowczak, Cichy, Rokita, & Domaradzki, 2021; Freitas, Pereira, Alcaraz, Comyns, Azevedo, & Loturco, 2022). However, statistically significant differences between soccer players and handball players in favour of soccer players were shown in the zig-zag test. Female soccer players had better values in this test, earlier research also supports the obtained result (Popowczak, Cichy, Rokita, & Domaradzki, 2021; Freitas, Pereira, Alcaraz, Comyns, Azevedo, & Loturco, 2022). The explanation for such results can also be seen in the lower centre of gravity, which is more characteristic of female football players (Hewitt, Norton, & Lyons, 2014; Mala, Maly, Zahalka, Bunc, Kaplan, Jebavy, & Tuma, 2015), both because of the longitudinal dimensionality of the skeleton and because of the sport approach, but also in the higher body mass, which is more present in handball players, which can affect the speed of mobility, i.e. changes in the direction of movement at maximum speed (Hewitt, Norton, & Lyons, 2014; Popowczak, Cichy, Rokita, & Domaradzki, 2021). Also, a statistically significant difference was observed in the explosive strength parameter, specifically in the CMJ test, which, when exercising this subspace of basic motor skills, has the characteristic of activating the whole body. The results showed a statistically significant advantage in the height of this jump among handball players. The data obtained in this way can be explained by the specificity of the handball game, which in its technical and tactical elements has a fair amount of jumps with a shot or passing the ball, which primarily affects the development of the explosive strength of the whole body, which was also confirmed in earlier research (Gorostiaga, Granados, Ibanez, & Izquierdo, 2005; Iacono, Eliakim, & Meckel, 2015; Cichy, Rokita, & Domaradzki, 2021).

In accordance with the aforementioned, the advantage of this study is reflected in the application of sophisticated cutting-edge technology for determining the value of the monitored parameters of basic motor skills in soccer and handball players. In addition to these advantages, it can be pointed out that the sample of participants consisted of elite soccer and handball players of the senior category. Furthermore, the strength

of this study lies in the fact that it encompassed a large number of physical fitness parameters, providing a detailed examination of this field among elite female athletes. Also, it should be emphasized that the same tests were used to assess the analysed motor skills, and that each of the motor fields was assessed in three different tests that included the same body segments. The obtained values enable completeness in providing information about the differences in the analysed fields of basic motor abilities for certain body segments in female competitors at the highest level of the senior category, which is important knowledge for fitness coaches in the formation of plans for basic motor preparation of players of different sports.

The limitations of this study can be reflected in the relatively small number of monitored players on whom the analysis was performed, that is, it would be recommended that a larger number of respondents be included in future research. Also, it is necessary to include a segmental analysis of body composition parameters because it is about sports where there is a difference in the dominance of the extremities used when performing sport-specific techniques. In addition to the above, as far as basic motor abilities are concerned, the inclusion of a larger number of motor fields would give an even more precise difference between these two groups of respondents-sports. While this study encompassed a large number of motor tests, adding additional tests could further enhance the comprehensiveness of the analysis. Since the focus is on physical fitness, future research could also include the assessment of cardiovascular endurance, as well as muscular strength and muscular endurance, to provide an even more complete insight into the differences between these athletes. By determining the limitations in more detail, it can be seen that the analysis of basic motor fields through field tests should cover both the upper and lower extremities as well as the whole body, as this would give a more complete insight into possible diversity.

Also, the surface on which the basic motor skills tests are performed, if they were the same, could have an even more precise effect on possible differences. This would create a complete picture within the basic motor area based on sport, level of competition and age selection. Such analysis could make it much easier for coaches and experts in the process of selection itself regarding the physical profiling of players for a certain sport, but also for fitness coaches who could have a lot of influence with their training plans on the preparation of athletes during certain levels of competitions and sports.

CONCLUSION

In conclusion, this study provides valuable insights into the differences in anthropometric and motor performance characteristics between elite female football and handball players. Significant differences were observed in body composition, with handball players being taller and heavier, while football players exhibited a higher percentage of muscle mass and lower body fat. These differences are likely influenced by the specific physical demands and tactical requirements of each sport. While there were no significant differences in sprinting performance, football players excelled in agility tests such as the zig-zag test, likely due to their lower centre of gravity and enhanced mobility. On the other hand, handball players demonstrated superior explosive strength in the countermovement jump with arm swing, reflecting the sport's emphasis on power for actions such as jumping and shooting. Our findings revealed that handball players were taller and heavier, while football players had a higher percentage of muscle mass and lower body fat, with football players excelling in agility and handball players demonstrating superior explosive strength. Overall, these findings emphasize the role of sport-specific demands in shaping athletes' physical and motor abilities, highlighting the importance of tailored training regimens to optimize performance in each discipline.

AUTHOR CONTRIBUTIONS

Conceptualization, M.S. and M.A.; methodology, D.R.; software, S.Đ. and B.K.; validation, I.J.; formal analysis, G.J.; investigation, D.R. and G.K.; resources, V.P.; data curation, M.A.; writing—original draft preparation, M.S. B.K.; writing—review and editing, S.Đ. and G.K.; visualization, M.S. and B.K.; supervision, M.S.; project administration, I.J. and V.P. All authors have read and agreed to the published version of the manuscript.

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Enhancing spin mastery in figure skating: A longitudinal case-control study on off-ice spin board training for rotational proficiency in young skaters

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ABSTRACT

Mastering fast and stable spins is a key challenge for young figure skaters. This study tested whether off-ice training using a spin board with gyroscopic feedback could improve spin performance in skaters aged 9 to 14. Over 36 months, we followed 40 skaters from Kazakhstan and Belarus. Half of the group used the spin board in addition to regular on-ice training, while the other half followed traditional training only. Skaters who used the spin board showed better results: faster rotation speeds (1,150 vs. 950 RPM; $p < .001$), earlier spin mastery (10.8 vs. 11.6 years; $p = .04$), and higher success rates in performance tests (78% vs. 62%; $p = .002$). Participants of this study self-reported feeling more confident during training and competition. In particular this paper includes a case study of the skater Mariya Sosnovskaya, who earned a top score of 101.89 points at a national event, demonstrating that the alternative training improved real-world performance. Our findings suggest that spin board training is a safe, practical, and effective way to help young athletes tremendously improve spin skills. Furthermore, it may also support confidence and reduce injury risks, making it a valuable tool for coaches and sports professionals.

Keywords: Performance analysis, Figure skating, Off-ice training, Gyroscopic feedback, Vestibular adaptation, Youth athletes, Rotational velocity.

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INTRODUCTION

According to the International Skating Union (ISU), spins are a critical component of competitive figure skating as they account for up to 20% of technical scores in ISU events (ISU, 2024). Moreover, upright and camel spins are particularly challenging as they demand precise technique as well as sustained rotational speeds ranging from 800 to 1,200 rpm. For skaters aged 9 to 14, these demands place significant stress on their still developing vestibular and proprioceptive systems, often leading to dizziness, balance difficulties, and heightened injury risk (Sands et al., 2012). As such research is needed to provide with novel solutions that can help support these young learners develop the needed skills without overburdening them physically or psychologically.

Despite the foundational nature of on-ice training, it suffers from several constraints such as limited ice time, physically taxing nature of repetitive complex elements, and bodily overuse which increase the frequency of injuries. It has been observed that such impediments related to traditional on-ice skating delay rather than aid skill acquisition and can lower the confidence of athletes during key stages of their growth. However, with recent innovations in off-ice training most of these issues can be addressed successfully.

As is documented in the study, the use of modified spin boards that allow for resistance adjustment and equipped with gyroscopic feedback systems offer a promising solution. These hybrid spin boards enable athletes to rehearse spin mechanics safely and consistently in a controlled environment. As a result, they allow the needed vestibular adaptation and technical refinement without the risks associated with high-impact, on-ice repetitions (Nakamura & Petrov, 2022).

Notwithstanding these benefits the efficacy of these tools and techniques has not been rigorously assessed in young skaters over an extended period. It is to address that deficiency that this study has been carried out so that baseline real-world data is available to inform further research and best practices in the domain of ice skating. This study addresses the existing research gap by presenting the first longitudinal evaluation of a structured spin board training program integrated with regular practice. Instead of completely substituting traditional practice, this study suggests a supplementary approach in order to retain the recognized benefits of traditional training while minimizing the potential for damage. By examining key performance indicators like rotational velocity, spin mastery age, execution success, and psychological confidence and using objective biomechanical measures and subjective athlete reports, this study aims at improving ice skating training significantly. Furthermore, by providing reliable, multi-dimensional evidence, the research makes a strong case for incorporating off-ice spin training into standard pathways for young figure skaters.

METHODS

Study design

This study follows a longitudinal controlled design and was carried out over a 36-month period (2022 to 2025). It aimed at evaluating the long term effects and benefits of off-ice spin board training in comparison to traditional programs with regards to rotational performance in young figure skaters. The participants included a total of 40 skaters, aged 9 to 14, who were selected from two established training centres in Ust-Kamenogorsk, Kazakhstan, and Minsk, Belarus. These specific locations were chosen for their track record and comparable athlete development programs and similar training environments.

To control for confounding variables which would otherwise lead to faulty associations between dependent and independent variables, participants were matched based on age, sex, and initial skill level. The skill level

match specifically focused on their proficiency in upright, sit, as well as camel spins. On one hand, the experimental group ($n = 20$) incorporated 3–4 off-ice training sessions per week using the hybrid modified spin board described before set to an 8 kg resistance. On the other hand, The control group ($n = 20$) continued their usual on-ice routines without any additional rotational training aids.

Ethical approval and participant recruitment

The research protocol followed by this study has been approved by the Kazakh National University Ethics Committee (Approval ID: KNU-2022-001 issued on February 1 2022). Also, all study procedures conform to the ethical guidelines of the Declaration of Helsinki. In line with the stated requirements, written informed consent was obtained from all participants' parents or legal guardians, and assent was secured from the athletes themselves. Utmost care was taken to ensure that all ethical parameters were taken care of meticulously.

The study ensured that eligible participants were actively competing at or above the 1st Sports Category level (or national equivalent) and demonstrated basic technical competency in the three standard spin types mentioned before. The exclusion criteria for this study included: previous exposure to spin boards as well as any diagnosed vestibular, orthopaedic, or neurological conditions. It was ensured that all participants went through a pre-participation medical examination and completed standard vestibular screening protocols to ensure suitability for rotational training.

Outcome measures

Primary outcome

The Rotational velocity (RPM) during camel spins was measured using a Vicon motion capture system (specifically sampling at 100 Hz, with an error margin of ± 0.5 RPM). The essential Data Collection occurred at four points in time: baseline, and consequently after 12, 24, and 36 months of the training (standard and modified).

Secondary outcomes

To maintain reliability of data, the Spin success rate, or the percentage of attempts achieving ≥ 3 full rotations, was evaluated by certified coaches using a consistent rating scale. The Intraclass Correlation Coefficient (ICC) which ranges from 0 to 1, was employed as a statistical measure to quantify the agreement between independent raters. During the study the ICC was found to be 0.90 which not just conforms inter-rater agreement but points towards "excellent reliability". In other words, this value (ICC = 0.90) adds to the reliability of the data since independent raters came to almost identical conclusions about participant performance.

Age of mastery: The age of mastery in this study was recorded as the age at which participants consistently met performance criteria for a technically correct camel spin.

Confidence levels: The study assessed level of confidence through semi-structured interviews and a 5-point Likert scale. These were adapted from widely-tested tools used in youth sports psychology. The participants' responses to the interviews were audio-recorded and thematically analysed to ensure a high standard of academic reliability and rigor.

Data collection and analysis

The Quantitative data collected during the study were analysed using independent t-tests as well as mixed-effects regression models. These helped track group differences over time while adjusting for key covariates

such as age, Tanner stage, and weekly training volume. On the other hand, for categorical variables such as spin success rate, Chi-square tests were used instead. The justification for the use of T-tests and mixed-effects regression in the first instance rests on the fact that they are best suited for continuous numerical data (RPM, training volume etc) as they are helpful when comparing average values between two groups which can change over time. On the other hand, Chi-square tests, which are more suited to data that is categorical were employed in this study for spin success rate which has a yes/no outcome and is hence categorical.

Missing values

The missing values in this study accounted for less than 5% of the data and were managed using multiple imputation techniques, following best-practice statistical methods. The low percentage of missing values suggests that data collection was thorough, with minimal disruptions or in gathering participant information during interviews. This complements the fact that the Interview transcripts were rigorously and carefully analysed using thematic analysis as outlined by Braun and Clarke (2006). Also, the coding was conducted by two independent researchers, who maintained an inter-coder reliability of >85%. This further points to the great care taken to ensure the accuracy and trustworthiness of qualitative insights in this study.

RESULTS

Baseline characteristics

Firstly, no significant differences between groups were observed at baseline, thus confirming effective matching (Table 1). Secondly, high adherence rates were noted during the study in both experimental and control phases; with experimental adherence of 92% and control adherence of 89%. Thirdly, the absence of spin-related injuries during modified training further underscores protocol feasibility and safety.

Table 1. Baseline demographic and training characteristics.

Characteristic	Experimental (n = 20)	Control (n = 20)	p-value
Age (years, mean $\pm$ SD)	10.4 $\pm$ 0.7	10.3 $\pm$ 0.6	.65
Female (%)	60%	55%	.75
Weekly Training Hours	7.2 $\pm$ 0.8	7.0 $\pm$ 0.9	.50
Baseline RPM	700 $\pm$ 50	700 $\pm$ 45	.98

Table 2. Comparative performance outcomes at 36 months.

Outcome	Experimental (n = 20)	Control (n = 20)	Statistical test
RPM at 36 months	1,150 $\pm$ 120	950 $\pm$ 130	$t(38) = 8.12, p < .001$
Success Rate (%)	78	62	$\chi^2(1) = 9.87, p = .002$
Mastery Age (years)	10.8 (95% CI 10.5–11.1)	11.6 (95% CI 11.3–11.9)	$t(38) = 4.23, p = .04$
Confidence Score (1–5)	4.2 $\pm$ 0.6	3.5 $\pm$ 0.7	$t(38) = 3.21, p = .003$

Primary and secondary outcomes

By the end of this study, the experimental group demonstrated a statistically visible and practically observable significant increase in camel spin rotational velocity (1,150 $\pm$ 120 RPM) compared to the control group which could not achieve comparable results (950 $\pm$ 130 RPM; $t(38) = 8.12, p < .001$, Cohen's $d = 1.56$). The study demonstrates how Spin Success Rates improved markedly (78% vs. 62%; $\chi^2(1) = 9.87, p = .002$), and while the age of mastery was reduced by an average of 0.8 years (10.8 vs. 11.6 years; $t(38) = 4.23, p = .04$) thus accelerating athletic growth and success. Additionally, the high Confidence scores reflected enhanced psychological readiness (4.2 $\pm$ 0.6 vs. 3.5 $\pm$ 0.7; $p = .003$) among the participants in the experimental group.

These results provide the tangible data to sufficiently demonstrate the efficacy of the spin board training protocol when employed for the training of young athletes in the field (Table 2).

Case study: Mariya Sosnovskaya

A key aspect of this academic study is the detailed observation of Mariya Sosnovskaya's progression which epitomizes the transformative potential of spin board training. Through a focused case study it was documented that Sosnovskaya who started her athletic journey at a spin velocity of 700 RPM and a 40% success rate at age 9, had, through the modified hybrid training suggested in this study, attained an outstanding Spin Velocity of 1200 RPM and an 80% success rate by age 11, culminating in a first-place finish at the VI Winter Spartakiad of the Republic of Kazakhstan 2025 with an outstanding score of 101.89 points. In contrast, her matched participant from the control group only achieved a spin velocity of 950 RPM, a 60% success rate, and only scored 90.00 points in the competition (Table 3). Furthermore, Qualitative interviews carried out with Sosnovskaya revealed increased spatial awareness, reduced dizziness, and heightened competitive confidence, thus confirming and supplementing the results of the quantitative analyses during the study.

Table 3. Case study comparison between Mariya Sosnovskaya and matched control.

Metric	Age 9 (Baseline)	Age 11 (Post-Training)	
RPM	700	1,200	
Success Rate (%)	40	80	
Competition Score	N/A	101.89	
Matched Control (Age 11)	RPM	Success Rate (%)	Competition Score
	950	60	90.00

DISCUSSION

Principal findings

This research study has successfully carried out and presented the findings of the first longitudinal study carried out to examine how off-ice spin board training with gyroscopic feedback can significantly accelerate the mastery of the camel spin in youth figure skaters. The study has collected reliable data and documented an impressive 200 RPM increase in rotational velocity as well as a significantly lower average mastery age which in turn points towards the effectiveness of the modified training in athletes' developmental progress. These gains stem from training protocol's emphasis on controlled, repetitive vestibular stimulation and motor learning while ensuring a safe and injury-free training environment that also taken into consideration young learner's psychological needs.

The competitive achievements of Sosnovskaya further support the applied value of the suggested intervention using modified spin boards to reduce the need for extensive and draining on-ice practice. The study has also furthered the cause advocated by previous research in the field and notably, effect sizes in this study exceed those reported in previous research on off-ice training modalities (Brown et al., 2020). It is also essential to mention that in addition to technical improvements, participants in the intervention group reported enhanced confidence which suggests that spin board training also contributes to building psychological resilience and performance readiness in young athletes in the field of figure skating.

Strengths and limitations

The study has demonstrated several strengths through qualitative and quantitative means which reinforce the findings. These strengths including the selection of a longitudinal design, the careful matching of

participants between the control and experimental group, high adherence to the training regimen, and the use of both objective and subjective outcome measures, especially with semi-structured interviews. The inclusion of a real-world case study offers further contextual support for the intervention's relevance to competitive performance.

However, the few limitations of this study that are inevitable, must be acknowledged. The sample size, while adequate for detecting key effects, limits the study's statistical power and future studies may work on larger sample sizes for greater validity. Also, some variation in coaching delivery, despite following the standardized protocols, is inevitable and could have influenced outcomes. Additionally, the study's regional scope due to being limited to two training centres, may contribute to reduced generalizability. Again, it is expected that future research with larger, more diverse samples across multiple training environments will address these limitation and provide more varied data.

Implications for practice and future research

The findings of this study suggest that off-ice spin board training using modified boards is a valuable supplement to conventional figure skating instruction, particularly for enhancing rotational skills in younger athletes. Further, the structured and safe format of this modified training makes it well-suited to youth development programs that aim at enhancing skill development and mastery while avoiding the risks involved with and the intense physical demands of repeated on-ice attempts during training.

In line with the findings of this study, future studies should explore the long-term effects of such training, as well as its role in injury prevention. Similarly focused research is need on the impact of this modified off-ice training on vestibular function and motor coordination. Ultimately, research across broader populations and skill levels will be essential to assess the general applicability of using off-ice training with modified spin boards and further studies are needed to refine its application in varied training environments.

CONCLUSION

The Off-ice spin board training with gyroscopic feedback, which was the main focus of this study, appears to be a promising supplement to traditional on-ice practice for young figure skaters. By supporting faster skill acquisition and greater psychological confidence on one hand, while reducing physical and psychological stress on the other, the hybrid training regime can help improve training outcomes in a safe and structured manner. The findings of this study are expected to contribute positively to growing research in support of evidence-based practices in youth sports, particularly to the highly competitive field of figure skating. However, further research will be needed to increase the generalizability and replication of this study beyond its current scope.

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No potential conflict of interest was reported by the author.

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Potential of sport and physical activity in academic resilience of university students

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ABSTRACT

Resilience is universally recognized as a strength or asset, representing a desirable and beneficial quality, trait, or process with the potential to positively influence various aspects of an individual's performance, achievement, health, and well-being. This concept holds particular significance in the context of sports. A cross-sectional research was used in this study with efforts to find out whether there are differences in resilience levels among students based on their sports participation and to determine potential socio-demographic factors contributing to academic resilience. The study involved 379 students from several state universities in the Republic of Serbia (76.0% female and 24.0% male), aged 18 to 30 years ($M = 21.67 \pm 1.98$). The Academic Resilience Scale (ARS) was used in the study, as well as a specific questionnaire for the purpose of this research, which contained inquiries about sociodemographic data of respondents and sport engagement. Results indicated that students engaged in sports show greater levels of academic resilience but there were no significant differences among students engaged in different type of sports (individual/group). The average grade of students was statistically significantly correlated with academic resilience levels. These results emphasize the importance of encouraging sports participation among students as a means to enhance both resilience and academic performance.

Keywords: Physical education, College students, Resilience, Sports, Academic achievement, ARS-30.

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INTRODUCTION

Students are a vulnerable category of the population facing numerous challenges, starting with the admission process to university. Many of them leave their parental homes and adapt to different living conditions, often in larger urban settings. They encounter new and more demanding academic requirements, establish new social connections, and many are in search of employment or already working, with some already having formed their own families. Experts from various fields and perspectives strive to illuminate numerous questions and uncertainties that students encounter. The completion of studies, as the ultimate goal of their academic journey, imposes a significant burden not only on the students themselves but also on their families. In this context, recent literature over the past two decades has seen a substantial number of authors analysing the topics of resilience and physical activity or sports engagement, both among students at faculties of sports and physical education and in the general student population.

High-quality education, especially higher education, is an important precondition for finding a job and success in the labour market, which further opens the possibility for career development and improving the quality of (Getzel et al., 2001). The students' engagement is an important factor for academic success and obtaining a university degree, which is confirmed by the results of numerous studies obtained by surveying students (Appleton et al., 2008; Kuh, 2001; Kuh, 2009; Maroco et al., 2016). Literature findings confirm the role of resilience in overcoming academic responsibilities (Yaure et al., 2020) and the World Health Organization (WHO) emphasizes the importance of engaging in physical activities and provides guidelines regarding the type of physical activity, the number of hours recommended for each age category, as well as the benefits (WHO, 2020).

As the concept of resilience is variously understood and defined in the literature (Radovanović et al., 2020), the concept of academic resilience is also subject to diverse interpretations and definitions. The most commonly cited definition of academic resilience, or resilience in academic contexts, is likely the probability that an individual, despite adversities faced, achieves success in educational or other circumstances (Fallon, 2010; Wang et al., 1994. in Tudor & Spray, 2018). Academic resilience is the ability of an individual to effectively cope with stress, pressure, and challenges in academic activities (Martin & Marsh, 2009). In this study, we adhere to the definition provided by the author Cassidy (2016), whose scale was utilized in the research, wherein academic resilience is characterized as an individual's capacity to navigate through temporary or persistent academic setbacks and overcome numerous adversities that jeopardize educational progress and success.

Resilience is universally recognized as a strength or asset, representing a desirable and beneficial quality, trait, or process with the potential to positively influence various aspects of an individual's performance, achievement, health, and well-being (Bartley et al., 2010. in Cassidy, 2016). This concept holds particular significance in the context of sports. Individuals participating in sports often face different stressors than non-athletic individuals (Pritchard & Wilson, 2005). Due to the presence of a highly evaluative environment, where outcomes are linked to both positive and negative consequences (Sarkar & Fletcher, 2014), these individuals face a diverse array of potential stressors, such as injuries, poor performance, and health issues (Arnold & Fletcher, 2021). These stressors have the potential to adversely affect athletes' mental well-being (Arnold & Fletcher, 2021). Given the nature of these challenges, resilience emerges as a fundamental psychological construct crucial for success (Durand-Bush et al., 2023). The crucial question is not whether athletes will confront adversity in sports, but rather how they will respond when faced with challenges (Galli & Gonzales, 2015).

Although the literature underscores a direct correlation between resilience and sports activities in university students (Cohu, 2005; Demir & Barut, 2020; Román-Mata, et al., 2020; Sarkar, & Fletcher, 2014; Xia, et al., 2020), findings also reveal that, in addition to a direct correlation, there is a mediating role between them, namely the needs for competence, autonomy, and belongingness (Xu et al., 2021), as well as the mediating role of internal motivation (Chacón-Cuberos et al., 2019). Findings from intervention-based studies also highlight the potential of structured physical and recreational programmes to enhance resilience in youth (Bloemhoff, 2006).

The aim of the present study was to determine the differences in academic resilience levels between active students, engaged in sports activities, and inactive students. The second aim of the research was to identify sociodemographic factors within the active student group that correlate with academic resilience levels.

MATERIALS AND METHOD

Participants

The study involved 379 students (see Table 1) from several state universities in the Republic of Serbia (76.0% female and 24.0% male), aged 18 to 30 years ($M = 21.67 \pm 1.98$). The largest group of respondents consisted of undergraduate students (89.2%).

Table 1. Sample characteristics.

		N	%
Gender	Male	91	24.0
	Female	288	76.0
Academic level	Undergraduate (Bachelor's)	338	89.2
	Graduate (Master's and Doctoral)	41	10.8
	First	57	15.0
	Second	92	24.3
Academic year	Third	113	29.8
	Fourth	45	11.9
	Extended	31	8.2
	Master's and Doctoral	41	10.8
Accommodation	Tenancy	191	50.4
	Student dorm	72	19.0
	Parents' or Relatives' accommodation	116	30.6

Instruments

The Academic Resilience Scale (ARS 30) (Cassidy, 2016) was used in the study. The scale has 30 items divided into three subscales: Perseverance (14 items), Reflecting and adaptive help-seeking (9 items), and Negative affect and emotional response (7 items). Items are scored on a 5-point Likert scale from probable (1) to unlikely (5). Students answer questions of the following type: *I would just give up, I would seek help from my tutors, I would probably get annoyed*, etc. Positively formulated items, such as e.g. *I would give myself encouragement*, are transformed so that high scores indicate greater resilience. Scores can be calculated for the three listed subscales as well as for the scale as a whole. The range of scores on a scale as a whole is from 30 to 150. Cronbach's α on a scale level is .83 indicating good reliability.

In addition to the ARS 30 scale, a specific questionnaire was constructed for the purpose of this research, which contained questions about sociodemographic data of respondents and sport engagement. The socio-

demographic data collected encompassed gender, age, average grade, academic level, academic year, and accommodation type. Regarding sports, the questions were formulated to collect data on respondents' participation in sports activities and the specific types of sports they engaged in. When asked about the type of sport, respondents provided open-ended answers, subsequently categorized into group (team) or individual sport.

Procedure

A cross-sectional research was used in this study with efforts to find out whether there are differences in resilience levels among students based on their sports participation and to determine potential socio-demographic factors contributing to academic resilience. The survey was conducted in 2021 via the Internet, in the form of a Google questionnaire. The participants were recruited voluntarily through an announcement posted in several student groups on the social media platform Facebook. The purpose of the research was clearly explained to the students, and they were requested to fill out the instruments honestly, providing relevant data and indicating their level of agreement with the provided statements. It was also emphasized that participants could withdraw from the research at any time if they chose to do so. Written consent from the students was obtained for the study, and the research was conducted entirely anonymously and voluntarily.

The obtained results were computed using IBM SPSS software version 26 for statistical data processing. For the data analysis, we used descriptive statistical parameters: frequencies (f), percentages (%), means (M), and standard deviations (SD). For data analysis, ANOVA and t-tests were used for group differences, and Pearson's and Spearman's correlations for determining correlations between academic resilience levels and sociodemographic characteristics.

RESULTS

Descriptive statistics of academic resilience levels regarding the three subscales (Perseverance, Reflecting and adaptive help-seeking, and Negative affect and emotional response) and the total score of ARS-30 of the whole sample are presented in Table 2.

Table 2. Descriptive statistics of academic resilience levels of the whole sample (N = 379).

	Theoretical range of scores	Min	Max	M	SD
Perseverance	14-70	37.00	70.00	54.81	6.35
Reflecting and adaptive help-seeking	9-45	16.00	45.00	34.24	5.52
Negative affect and emotional response	5-35	11.00	35.00	24.35	5.17
Total score	30-150	72.00	145.00	113.40	13.17

The mean scores presented in Table 2 suggest that students from our sample exhibit moderately high levels of academic resilience across all subscales as well as the total score. High scores indicate a generally resilient student population as a whole, capable of effectively handling academic challenges that they confront.

Academic resilience in the context of sports

The first objective focused on investigating differences between resilience levels among students based on their involvement in sports activities. The results of the t-test are presented in Table 3.

Table 3. Differences on the academic resilience scale regarding engagement in sports.

	Group	M	SD	SE _M	t(377)	p-value	d
Perseverance	Active (N = 234)	55.62	6.32	0.41	2.94	.003	.11
	Inactive (N = 145)	53.65	6.39	0.53			
Reflecting and adaptive help-seeking	Active (N = 234)	34.51	5.60	0.37	1.12	.26	.11
	Inactive (N = 145)	33.86	5.46	0.45			
Negative affect and emotional response	Active (N = 234)	24.83	5.06	0.33	2.23	.03	.11
	Inactive (N = 145)	23.62	5.27	0.48			
Total score	Active (N = 234)	114.97	13.28	0.87	2.75	.01	.11
	Inactive (N = 145)	111.12	13.15	1.09			

According to the t-test results presented in Table 2, there are significant differences for Perseverance ($p = .003$), Negative affect and emotional response ($p = .03$), and the total score ($p = .01$), where students engaged in sports demonstrate higher levels of resilience. No statistically significant differences were found for the subscale Reflecting and adaptive help-seeking ($p = .26$).

Based on the presented results, differences in resilience related to engagement in sports are evident. Therefore, our next objective was to investigate whether there are differences based on the type of sport. Considering that the research included a large number of students engaged in various types of sports, we classified participants into those engaged into individual and group (team) categories. The t-test results are displayed in Table 4.

Table 4. Differences on the academic resilience scale regarding the type of sport.

	Group	M	SD	SE _M	t(232)	p-value	d
Perseverance	Individual (N = 184)	55.41	6.26	0.46	-1.17	.24	.16
	Group (N = 50)	56.58	6.33	0.90			
Reflecting and adaptive help-seeking	Individual (N = 184)	34.66	5.93	0.44	0.43	.67	.16
	Group (N = 50)	34.28	4.10	0.58			
Negative affect and emotional response	Individual (N = 184)	24.72	5.17	0.38	-0.77	.44	.16
	Group (N = 50)	25.34	4.68	0.66			
Total score	Individual (N = 184)	114.78	13.69	1.01	-0.67	.50	.16
	Group (N = 50)	116.20	11.32	1.60			

Although the previous analysis demonstrated that students engaged in sports exhibit higher levels of resilience on two out of three subscales and the overall score, the results indicate that there are no such differences concerning the type of sport. According to the data from Table 4, no statistically significant differences were found in resilience levels between students engaged in individual sports and those participating in team sports ($p > .05$).

Academic resilience in the context of sociodemographic characteristics

Since our previous analyses showed that students actively engaged in sports show greater levels of academic resilience, our next aim was focused on determining differences in sociodemographic characteristics of students who are engaged in sports.

First of all, we wanted to examine whether there are differences in resilience levels between male and female students who are engaged in sports activities. The results are presented in Table 5.

Table 5. Differences between male and female students on the academic resilience scale.

	Group	M	SD	SE _M	t(241)	p-value	d
Perseverance	Male (N = 78)	54.64	7.23	0.82	-1.61	.11	.14
	Female (N = 165)	56.02	5.67	0.44			
Reflecting and adaptive help-seeking	Male (N = 78)	33.45	6.20	0.70	-2.05	.04	.14
	Female (N = 165)	35.01	5.21	0.41			
Negative affect and emotional response	Male (N = 78)	25.53	5.06	0.57	1.49	.14	.14
	Female (N = 165)	24.49	5.08	0.40			
Total score	Male (N = 78)	113.62	14.97	1.70	-1.06	.29	.14
	Female (N = 165)	115.52	12.09	0.94			

Based on the t-test results presented in Table 4, the only significant difference is observed in the Reflecting and adaptive help-seeking ($p < .04$), indicating that females have higher scores than males. There were no other significant differences in the academic resilience scores regarding gender ($p > .05$).

Our next aim was focused on examining resilience levels in relation to the sociodemographic characteristics of active participants. First of all, we wanted to examine whether resilience improves with the age of participants, their academic level, their academic year, and their average grades. Pearson's correlation was used to determine the correlation between academic resilience levels and age, while Spearman's correlation was used to determine the correlation with academic level, academic year, and average grade. The results are presented in Table 6.

Table 6. Correlations between academic resilience and age, academic level, academic year, and average grade.

	Perseverance	Reflecting and adaptive help-seeking	Negative affect and emotional response	Total score
Age	-.11	-.11	-.02	-.11
Academic level	-.04	-.02	.01	-.03
Academic year	-.08	-.04	-.05	-.06
Average grade	.19*	.18*	.09	.21**

Note. * - Significance level at $p < .05$; ** - Significance level at $p < .01$.

Table 7. Differences in academic resilience levels in relation to the type of accommodation.

	Type of accommodation	N	M	SD	F	df	p-value
Perseverance	Tenancy	118	55.93	6.46	0.53	2	.59
	Student dorm	49	55.63	6.20			
	Parents' or relatives' accommodation	76	54.99	5.93			
Reflecting and adaptive help-seeking	Tenancy	118	34.51	6.07	0.48	2	.62
	Student dorm	49	35.12	5.77			
	Parents' or relatives' accommodation	76	34.12	4.63			
Negative affect and emotional response	Tenancy	118	24.36	5.27	0.98	2	.38
	Student dorm	49	25.16	5.02			
	Parents' or relatives' accommodation	76	25.33	4.82			
Total score	Tenancy	118	114.80	13.88	0.20	2	.82
	Student dorm	49	115.92	13.97			
	Parents' or relatives' accommodation	76	114.43	11.22			

As shown in Table 6, correlation analyses revealed that there were no statistically significant correlations when it came to the age of the participants, academic year, or their academic level ($p > .05$). When it comes to the average grade of participants, very weak positive correlations were noted with Perseverance ($r_s = .19$) and Reflecting and adaptive help-seeking ($r_s = .18$), while a weak correlation was noted with the total score ($r_s = .21$). The correlations between these variables indicate that with the higher grade, there's also an increase in resilience levels regarding Perseverance, Reflecting and adaptive help-seeking, and total resilience scores.

We also wanted to investigate whether the resilience levels were different between students living in different types of accommodation. Descriptive measures and ANOVA results are shown in Table 7.

As presented in Table 7, ANOVA analysis showed no significant differences in academic resilience levels between students living in tenancy, student dorms, and parents' and relatives' accommodation ($p < .05$).

DISCUSSION

The objectives of the research were to examine academic resilience in students in relation to engagement in sports and physical activity and their sociodemographic characteristics.

Similar to the results of previous studies (Lipowski et al., 2016; Wiedenman et al., 2023), our results indicated that students engaged in sports show greater levels of academic resilience. The results also showed that the type of sport (individual/group) was not statistically significantly correlated with academic resilience. From these results, it can be noticed that academic resilience is tightly connected to sports participation in general, but not that much to the type of sport itself. Other studies also confirm that there are no significant differences found in resilience levels between individual and team sport athletes (Bingol & Bayansalduz, 2016; Blanco-García et al., 2021; Boghrabadi et al., 2015; Onturk et al., 2020). Since athletes need to develop themselves in competitive settings, regardless of whether they participate in team or individual sports, resilience emerges as a crucial part of those settings (Bas & Gundogdu, 2021). Unlike in other fields, e.g. healthcare workers, athletes voluntarily opt to demonstrate resilience traits as a means of preserving their performance despite potentially challenging circumstances (Fletcher & Sarkar, 2012; Sarkar, 2017). It is believed that certain behaviours can be generalized from sports into academic areas. Participation in athletic activities implies adherence to rules of fair competition, a willingness to work with others for common goals, and the ability to persist during losses. Thus, these behaviours can provide rational tools for greater academic efforts (Braddock et al., 1991).

When it comes to the socio-demographic characteristics of participants, we tested whether there are differences between male and female students in academic resilience levels. The results showed that female students had better reflect and adaptive-seeking behaviours than male students. However, there is no clear consensus on which gender is more willing to seek help. Some findings indicate that females tend to seek psychological help more often than males (Nam et al., 2010) and also show higher resilience scores (Shenu & Mokgwathi, 2008), although other studies suggest they may seek help less frequently due to exhibiting shy behaviours (Molla, 2022). While female students from our sample may exhibit better adaptive behaviours and resilience in academic settings, their tendencies regarding seeking help can vary depending on the context and the type of assistance needed.

We also tested whether the age of participants, their average grades, academic levels, and academic years are correlated with academic resilience levels. Similar to the gender variable, there still remains a lack of

clear consensus regarding the connection between age and resilience levels within the sporting context. In this research, we found no significant correlations between age and academic resilience levels. These findings are in line with some research findings (Chacón-Cuberos et al., 2021; Onturk et al., 2020; Togo et al., 2018), while others found that higher levels of resilience are evident among older athletes (Blanco-García et al., 2021; Codonhato et al., 2018). Concerning the maturity of participants, our results showed that there are no significant correlations between resilience and academic levels, nor with academic years. Assuming that resilience develops gradually over time, it is reasonable to expect that older participants, not only in age but also in terms of higher years and academic levels, have confronted a wider range of challenges during time that can potentially boost their resilience levels. Hunter (2012), for example, suggests that students who are closer to graduation might experience higher anxiety levels since they transition into a phase where they will take greater responsibilities as adults. The variability in the research findings could stem from the diverse personal and social characteristics of individuals rather than simply their age or life phase.

Our results also showed that the average grade of students is statistically significantly correlated with academic resilience levels, indicating that students with higher average grades show greater levels of academic resilience. These findings align with previous studies (Abubakar et al., 2021; Tope-Banjoko et al., 2020). Based on these results it seems that resilient students tend to exhibit better learning and stress-coping abilities, which, in turn, contribute to higher academic achievements. It is possible that students who achieve higher grades possess certain attributes such as effective stress management, perseverance, and adaptability, which are indicative of higher levels of resilience. This reciprocal relationship suggests that fostering resilience among students could be beneficial for enhancing their academic achievements.

Lastly, we aimed to verify whether students living in different types of accommodation exhibit different academic resilience levels. Analyses showed no significant differences between students living in tenancy, student dorms, and parents' and relatives' accommodation. It is essential to note that while our study did not find significant differences in academic resilience levels among students living in various types of accommodation, other studies have reported contradictory findings. Khoroshikh and Andreeva (2019) observed that students living in dormitories exhibited higher levels of psychological distress compared to those living in tenancy or with their parents. Furthermore, Avila and Acena (2020) identified high levels of resilience among students living with their parents. These differences in results could be attributed to various factors, including cultural differences, socio-economic backgrounds, and the specific measures used to assess resilience and psychological distress.

This research has certain limitations, in addition to a smaller sample size, the results of engagement in sports activities relied on the participants' self-perception. Based on their engagement in sports activities, students from our sample were categorized into two groups: active and inactive. The active group included students who trained three or more times per week. In a study conducted by Román-Mata et al. (2020), student engagement in physical activities was classified according to WHO guidelines. Their findings indicated that meeting the minimum recommended duration of 150 minutes of physical activity per week is correlated with enhanced levels of resilience among students. Further, it is also necessary to examine wider contextual factors that could contribute to academic resilience levels in students. Future research should focus on examining the mediating role of internal factors, such as motivation, expectations, and self-efficacy, as well as risk and protective factors (Bostani, & Saiari, 2011; Chacón-Cuberos et al., 2019; Gupta, & McCarthy, 2022; Xia et al., 2020; Hill et al., 2021; Xu et Yang, 2024).

CONCLUSION

The findings of the study confirm that students who participate in sports exhibit higher levels of resilience across all domains. Among the examined sociodemographic variables, a higher level of resilience was found in some domains among female participants. There was also a positive correlation between resilience levels and higher average academic grades.

These results emphasize the importance of encouraging sports participation among students as a means to enhance both resilience and academic performance. Future research should explore some underlying mechanisms that could contribute to the increased resilience levels observed in students who are athletes, as well as investigate the impact of different types of physical activities and other sociodemographic factors. Longitudinal studies could also provide additional insights into the long-term effects of continuous engagement in sports on both resilience and academic achievements.

AUTHOR CONTRIBUTIONS

Ana Drobac (corresponding author) made substantial contributions to the conception of the work, acquisition and analysis of data, translation, and preparation for publication. Vesna Radovanović (co-author) made substantial contributions to the conception of the work, as well as to data analysis and interpretation. Jasmina Kovačević (co-author) made significant contributions to the conceptualization of the theoretical framework and the analysis of the literature.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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Effects of an instructional handball programme on motor and social skills in a secondary school: A randomized study with qualitative-quantitative design

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ABSTRACT

To evaluate the effectiveness of a school handball project in improving motor and social skills among secondary school students, using a mixed-methods randomised experimental design. 300 students aged 11-13 years were recruited and randomly assigned to an experimental group ($n = 150$) and a control group ($n = 150$). The experimental group followed a 12-week handball educational-sports programme, integrating practical and reflective activities. The control group performed traditional motor activities. Standardised motor tests (20m sprint, precision throwing, coordination test), questionnaires on social cooperation and qualitative focus groups conducted at the end of the intervention were used. The experimental group showed statistically significant improvements in motor performance ($p < .01$) and social cooperation ($p < .05$). The qualitative analysis showed increased motivation, inclusiveness, group cohesion and respect for rules. The integration of handball as a structured and intentional activity in the school context improves motor and social development in middle school students. These findings are consistent with the recent literature on the use of sport technologies and methodologies to optimise motor and cognitive performance (Latino & Tafuri, 2024), and support the idea that physical education should be intentionally designed to maximise cross-curricular learning impacts.

Keywords: Physical education, Handball, Sport, School, Experimental group.

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INTRODUCTION

In recent decades, physical education has been progressively recognised as an essential component of integral student development, not only for its benefits in terms of physical health, but also for its impact on cognitive, affective and relational dimensions (Bailey et al., 2009; WHO, 2020). Indeed, numerous international research studies have highlighted how regular participation in well-designed motor activities can positively influence adolescents' self-efficacy, ability to cooperate, emotional self-regulation and social identity (Ennis, 2017; Deci & Ryan, 2000). Despite this theoretical recognition, the Italian school context continues to show some resistance in fully integrating physical education within the educational curriculum. The discipline is often perceived as ancillary to traditional subjects, with negative repercussions on both the quality of teaching and student involvement (Cothran & Ennis, 1999). In many cases, the motor activities proposed are routine, unintentional and poorly connected to broader educational objectives, limiting the transformative potential of the sports experience.

In response to these critical issues, there has been a growing focus on the intentional use of team sports as an educational tool. The latter, by their very nature, require interaction, role management, cooperation and conflict resolution, configuring themselves as true experiential learning contexts (Hastie et al., 2011; Dyson, 2014; Johnson & Johnson, 2009). Shared action and the need to coordinate movements and intentions foster positive interdependence between peers and the construction of a collective identity.

Among the various collective disciplines, handball stands out for its particularly effective didactic-pedagogical profile. It is a dynamic sport with a high decision-making rate, requiring frequent role changes, rapid reading of situations and continuous tactical adaptation. These characteristics, in addition to developing conditioning and coordination skills, stimulate strategic thinking skills, operational autonomy and effective communication (Granados et al., 2007; Ortega et al., 2020; Praxedes et al., 2016). Furthermore, handball is easily adaptable to different school spaces and ability levels, making it accessible to less experienced or less motivated students.

In parallel, the pedagogical literature has proposed innovative models for teaching sport that go beyond the traditional technical-linear approach. In particular, models such as the Teaching Games for Understanding (TGfU) (Bunker & Thorpe, 1982) and the Sport Education Model (Siedentop et al., 2011) emphasise situated learning, reflection, responsibility and the personal meaning of motor experience. In these approaches, the post-activity reflective moment is not an accessory, but a central element of the educational process, fostering awareness, self-assessment and internalisation of shared norms and values (Schön, 1983; Casey & Goodyear, 2015).

This is coupled with a growing appreciation of mixed research methods (mixed methods), which combine quantitative and qualitative data to offer a richer and deeper insight into educational phenomena (Creswell & Plano Clark, 2017). In the motor field, such an approach allows for the objective measurement of performance progress and, at the same time, an understanding of students' experiences, their motivations, emotions and interpersonal dynamics. It is precisely from this integrated perspective that the educational benefits of consciously and reflectively designed school sports strongly emerge.

In particular, recent Italian studies (Latino & Tafari, 2024; Tafari et al., 2025) have shown how structured school sport interventions can generate significant improvements not only in terms of motor performance, but also in self-esteem, motivation and inclusion. Such evidence supports a view of sport as a complex educational device, capable of acting transversally on several dimensions of development.

However, despite the extensive theoretical and methodological apparatus supporting these practices, empirical research applied to secondary school, and focused on specific disciplines such as handball, is still lacking. In particular, there is a lack of controlled studies that assess with methodological rigour the effects of school sports programmes designed according to innovative didactic models.

The present study aims to fill this gap by systematically investigating the impact of a handball-centred educational-sports intervention on motor and social skills in pre-adolescent students. By means of a randomised experimental design and the use of mixed data collection instruments, it is intended to make a robust contribution to the literature on school motor education and to propose replicable operational guidelines for teachers and educational institutions.

Objectives

The main objective is to evaluate the effectiveness of an educational-sports intervention based on handball in the context of secondary school. In particular, it is intended to:

- Measure the improvement of specific motor skills (speed, coordination, precision);
- Assess the increase in social-relational skills (cooperation, respect, inclusion);
- Explore students' perceptions of sporting activity and group dynamics;
- To provide replicable methodological indications for handball teaching in schools.

METHODOLOGY

Study design

The study adopted a randomised experimental design with a qualitative-quantitative approach (mixed methods) to ensure a holistic view of the intervention outcomes. The research protocol was developed according to the PRISMA guidelines for educational studies and the CONSORT recommendations for school-based interventions (Moher et al., 2010).

The sample consisted of 300 students, selected from three comprehensive schools in the province of Naples. The students were stratified by age, gender and initial motor level, and then randomly assigned to two groups:

- Experimental group (n = 150): participated in the handball project;
- Control group (n = 150): followed the normal motor education activities included in the curriculum.

Inclusion criteria

To ensure the homogeneity of the sample and the internal validity of the study, precise inclusion criteria were established, consistent with the methodological and pedagogical objectives of the intervention. In particular:

- **Age between 11 and 13:** this age group was selected as it corresponds to the pre-adolescence period, a critical phase for motor and socio-emotional development. At this stage, students are sufficiently mature to understand and actively participate in structured teaching proposals, but are also particularly receptive to educational stimuli involving the relational and cooperative sphere.
- **Regular attendance in PE lessons (at least 80% attendance):** this criterion was adopted to ensure adequate exposure to the intervention and reduce variability due to the lack of continuity. Only students with constant attendance could benefit from the full course, an essential element to reliably assess the effects of the programme.
- **Absence of cognitive or motor disabilities that prevented active participation:** The aim of the study was to evaluate the effectiveness of a standardised sports teaching intervention. Therefore, it was necessary to exclude students with conditions that would have required significant adaptations

to the protocol or would have altered the balance of the groups. This choice does not imply a denial of the value of inclusion, but responds to the methodological need to maintain consistency in the experimental conditions.

- **Informed consent signed by parents or legal guardians:** voluntary and informed participation is a fundamental ethical prerequisite for conducting studies with minors. Consent ensured the transparency of the project and respect for the participants' rights, in line with current regulations on educational research.

Taken together, these criteria made it possible to select a sufficiently homogenous sample, representative of the target school population, and suitable for drawing reliable conclusions on the effectiveness of the proposed intervention.

Intervention

The educational intervention consisted of a 12-week course, divided into two weekly meetings of 60 minutes each, for a total of 24 units. The project was constructed on the basis of an integrated approach, in which the technical-tactical teaching of handball was constantly intertwined with educational strategies oriented towards social-relational development. This was inspired by the internationally recognised models of Teaching Games for Understanding (TGfU) (Bunker & Thorpe, 1982) and Sports Education (Siedentop et al., 2011), both of which focus on active learning, reflection and responsible participation.

Each session opened with a playful-motor activation phase, in which dynamic warm-up exercises and preparatory games were proposed. The aim was not only to prepare the students physically, but also to foster peer interaction, stimulating coordination, attention and a collaborative spirit from the very first minutes. This was followed by a central technical phase, dedicated to learning and consolidating the fundamentals of handball - passing, dribbling, shooting, marking - proposed in a gradual and adaptive form, taking into account the initial level of the participants.

The distinctive element of the intervention, however, lay in the subsequent phases, in which the skills learnt were transferred to semi-structured game contexts. Through simplified tactical situations (e.g. 2vs1 or 3vs2) and themed games (e.g. with compulsory role rotation or shared objectives), the students were called upon to make quick decisions, communicate effectively and coordinate with teammates. These forms of play, based on principles of cooperation and tactical problem solving, proved effective not only on a technical level, but also in the development of strategic thinking and shared responsibility (Harvey & Jarrett, 2014).

At the end of each lesson, a structured space was dedicated to collective reflection. Guided by the teacher, students were invited to share their perceptions, difficulties, strategies adopted and relational dynamics experienced during the activity. This moment - inspired by Schön's (1983) reflective pedagogy and the narrative practices proposed in the field of educational sport (Casey & Goodyear, 2015) - proved to be essential for promoting awareness, self-assessment and internalisation of the content learnt.

Particularly relevant was the choice of handball as the central discipline. In addition to its technical accessibility and adaptability to small spaces, handball has characteristics that make it pedagogically valuable: high frequency of interactions with the ball, rapid role rotation, complex cognitive demands and team dynamics that require constant collaboration. Recent studies confirm the effectiveness of school handball in developing not only conditional and coordinative skills, but also social skills such as respect for rules, positive communication and group management (Ortega et al., 2020).

In line with this evidence, the project included the extensive use of mini-game formats (3vs3, 4vs4) to ensure a high density of involvement. This type of organisation not only fostered the active inclusion of all students - even the less gifted - but also stimulated the development of collaborative forms of leadership, as already highlighted in the literature on sports education (Praxedes et al., 2018).

A key element was also the involvement of teachers, who took part in a six-hour intensive training module. This course alternated theoretical moments - focusing on teaching methodologies, managing group dynamics and the educational aims of sport - with practical sessions of micro-teaching and mutual observation. The intention was to provide operational tools for planning, managing and evaluating the intervention in a conscious manner and consistent with the stated objectives.

Finally, the entire project structure was in keeping with the European guidelines on physical education (EUPEA, 2019), which promote a vision of motor practice as an integrated educational experience, capable of contributing to the overall development of the person. The intervention, although centred on a specific sports discipline, was proposed as a transversal training device, capable of affecting motor, cognitive and socio-emotional aspects in a synergic and intentional manner.

Data collection tools

Quantitative:

- Eurofit test: standardised assessment of speed (20m sprint), explosive strength (medicine ball throw), dynamic balance (flamingo test), motor coordination (lateral jump on unstable axis) (Hardy et al., 2013);
- Psychosocial questionnaire: 5-point scale to measure cooperation, compliance with rules, leadership, peer support (Weiss & Ferrer-Caja, 2002).

Qualitative

- Focus groups: conducted with 36 students (12 per school), selected to represent different experiences. The interviews investigated motivation, relational dynamics, emotions felt during the activities;
- Systematic observations: recorded by two experienced observers on a predefined behavioural grid, focusing on 5 categories (positive communication, mutual aid, respect for rules, involvement, autonomous decision-making).

Qualitative data analysis

The data collected through focus groups and systematic observations were analysed through thematic analysis (Thematic Analysis), following the model proposed by Braun and Clarke (2006), which allows for the systematic identification, organisation and interpretation of significant patterns within the narrative data. The process consisted of six stages:

1. Familiarisation with the data (repeated reading of transcripts);
2. Generation of initial codes (open coding of relevant sentences and segments);
3. Theme search (aggregation of codes into conceptual cores);
4. Review of themes (checking internal and external consistency of identified themes);
5. Definition and naming of themes (attribution of meaning to emerging patterns);
6. Drafting of the final report (selection of representative citations and triangulation with quantitative data).

The analysis was conducted manually by two researchers independently, with subsequent discussion and consensus on the emerging themes to ensure intersubjective reliability. In line with the mixed educational research approach (Creswell & Plano Clark, 2017), a transformative and interpretive logic was adopted, aimed at bringing out the significance of students' experiences with respect to perceived changes in motivation, social interaction and group dynamics.

RESULTS

Quantitative results

The data collected by means of the standardised tests showed statistically significant differences between the experimental group and the control group in terms of both motor skills and social skills. In particular, the group that participated in the handball programme recorded substantial improvements in all areas tested: speed, explosive strength, coordination and social-relational dimensions. The following tables summarise the results obtained.

Table 1. Comparison between experimental and control group in motor tests (pre-post intervention).

Motor test	Group	Pre-test (mean $\pm$ SD)	Post-test (mean $\pm$ SD)	Δ % Improvement	Significance
20m Sprint (sec)	Experimental	4.35 $\pm$ 0.52	3.83 $\pm$ 0.47	-12%	$p < .01$
	Control	4.32 $\pm$ 0.49	4.30 $\pm$ 0.50	-0.5%	ns
Launch Accuracy (m)	Experimental	3.40 $\pm$ 0.61	4.01 $\pm$ 0.59	+18%	$p < .01$
	Control	3.45 $\pm$ 0.58	3.62 $\pm$ 0.55	+5%	ns
Coordination (no. jumps)	Experimental	18.0 $\pm$ 2.5	20.7 $\pm$ 2.2	+15%	$p < .01$
	Control	18.3 $\pm$ 2.4	19.0 $\pm$ 2.3	+4%	ns

Table 2. Scores of the socio-relational questionnaire (Scale 1-5).

Size	Group	Pre-test	Post-test	Δ Improvement	Significance
Cooperation	Experimental	3.2	4.4	+1.2	$p < .05$
	Control	3.3	3.5	+0.2	ns
Compliance with rules	Experimental	3.0	4.1	+1.1	$p < .05$
	Control	3.1	3.3	+0.2	ns
Positive leadership	Experimental	2.9	4.0	+1.1	$p < .05$
	Control	2.8	3.1	+0.3	ns
Peer support	Experimental	3.1	4.3	+1.2	$p < .05$
	Control	3.0	3.4	+0.4	ns

The data show a clear positive effect of the educational handball programme on the development of motor skills and social skills, confirming the effectiveness of the intervention in a real school context.

Qualitative results

The qualitative analysis allowed a more in-depth examination of the subjective and relational outcomes of the intervention, offering a more multifaceted view of the change observed in the participants of the experimental group. Through the processing of the data that emerged from the focus groups and systematic observations, five main areas of transformation were identified:

Increased motivation and interest in motor activity

The students involved in the handball programme showed high emotional and cognitive participation, with a progressive increase in intrinsic motivation. The playful-structured context, combined with the variety of

teaching proposals, fostered active involvement even among those who initially showed less interest in physical activity. The possibility of experimenting with different roles, in a non-competitive but cooperative climate, helped to strengthen the perception of self-efficacy.

Improved management of conflict dynamics

The shared sports experience, based on clear rules and cooperative tasks, facilitated the emergence of self-regulation and conflict resolution strategies. Students progressively developed a greater ability to deal with relational differences proactively, resorting to dialogue and negotiation. The concluding reflective moment acted as a space for the elaboration and consolidation of these strategies, promoting a culture of shared responsibility.

Development of collaborative leadership skills

During the activities, behaviours emerged that can be traced back to forms of distributed leadership, based on mutual support and the enhancement of each group member's contribution. Several students, even among those who did not usually assume central roles, showed initiative, organisational skills and attention to the inclusion of peers. This type of leadership was particularly evident in alternating-role situations, where dynamic and horizontal coordination was required.

Strengthening group cohesion and social integration

The project contributed to the strengthening of interpersonal bonds and the creation of a more cohesive classroom climate. The structured interaction in small groups, combined with the shared objectives of the activities, promoted collaboration even among students belonging to usually distinct social subgroups. In many cases, a broadening of peer relationships was observed, with greater openness and acceptance of individual differences.

Consolidation of autonomy and reflective thinking

The systematic introduction of debriefing at the end of each session stimulated in the students a reflective attitude towards their own actions, group dynamics and personal learning. This process fostered the development of metacognitive awareness, with observable repercussions also in decision-making skills during the game. Management autonomy manifested itself both in the autonomous resolution of tactical situations and in the ability to self-regulate in compliance with rules and assigned roles.

Systematic observations

The observations carried out in a natural context confirmed the evidence that emerged from the focus groups. In particular, a significant increase was noted in five behavioural areas: positive communication, peer support, respect for rules, active involvement and autonomous decision-making. These behaviours were recorded with greater frequency and intensity in the experimental group than in the control group, especially during cooperative play. This qualitative analysis provides an essential contribution to understanding the transformative scope of the intervention. The changes observed are not limited to performance aspects, but invest the relational, affective and identity levels, confirming the educational value of a structured, reflective and inclusive sports approach.

DISCUSSION

The results obtained confirm the validity of using an educational handball programme in the school context to foster motor and social development. Statistical analysis showed significant improvements in basic motor skills, as well as in social cooperation scores. These data are consistent with literature that emphasises that

participation in team sports can improve perceived self-efficacy and relational dynamics, especially in pre-adolescence (Tafari et al., 2025). The presence of cooperative activities, respect for rules, role rotation and post-activity reflection are crucial for students' social growth. As also demonstrated in the study conducted by Tafari et al. (2025) on the implementation of inclusive water polo with deaf adolescents, the adapted sports environment fostered clear improvements not only in motor skills, but also in self-perception, in peer integration and identity construction. The results that emerged reinforce the idea that physical activity, if designed with educational and inclusive aims, can represent a powerful training device for promoting the integral development of students. In this sense, our work follows in the wake of the innovative experiences also documented by Morsanuto et al. (2023), who demonstrated how an integrated sports education programme, centred on outdoor activities and adapted football for children with autism spectrum disorder, can foster significant progress on the motor, social and cognitive levels, concretely contributing to the achievement of the Sustainable Development Goals of Agenda 2030, in particular those related to health, quality education and the reduction of inequalities (SDGs 3, 4, 10). As also demonstrated in the experimental study conducted by Tafari et al. (2025) on the implementation of an inclusive water polo programme for deaf adolescents, participation in structured sports with communicative and methodological adaptations generated significant improvements not only in motor skills, but also in perceived self-efficacy and the quality of peer relationships. These results reinforce the evidence that adapted sport is a powerful tool for school inclusion and overall development, even in the presence of sensory barriers.

The use of inclusive methodologies, mediated by alternative communication tools and cooperative learning strategies, demonstrates the effectiveness of sport as a vehicle for integrated and multidimensional education. Such evidence reinforces the concept of sport as a transversal educational tool, useful not only for the development of motor skills, but also for the formation of the whole person.

CONCLUSIONS

The present study has shown that a handball-based sports education programme, intentionally designed and based on cooperative educational models, can produce significant improvements in students' motor skills and social-relational competences. These results support the hypothesis that physical education should be considered as a privileged field for the integral development of the person, acting in a transversal way on cognitive, emotional and relational aspects (Bailey et al., 2009; Ennis, 2017). The transformations observed in the experimental group, both in terms of performance and motivation, highlight the formative potential of motor activities when accompanied by conscious reflection and planning. Consistent with the principles of Social and Emotional Learning (SEL) and the indications of Latino & Tafari (2024), the systematic integration of educational sport within school curricula is recommended. In line with these findings, integrated school interventions combining motor and nutritional education have shown effectiveness in preventing eating disorders and improving overall psycho-physical well-being (Gravino et al., 2025), reinforcing the proposal for a multidimensional educational model. In perspective, the collaboration between schools and school medical services can further strengthen the effectiveness of these interventions, contributing to the prevention of discomfort and the promotion of students' overall well-being (Tafari & Latino, 2024).

The improvement in motor skills, documented through standardised tests, goes hand in hand with more complex and subtle transformations that emerged from focus groups and systematic observations: increased intrinsic motivation, cooperation skills, conflict management, development of reflective thinking and strengthening of group cohesion. These changes are not isolated episodes, but coherent manifestations of an educational process centred on active participation, appreciation of experience and social learning.

It is to be hoped that future research will evaluate the long-term impact of such interventions as well as their replicability in heterogeneous educational settings. A school that promotes physical activity as a multidimensional learning experience actively contributes to building resilient, aware and socially competent citizens.

AUTHOR CONTRIBUTIONS

The authors noted that there was equal participation in the elaboration of this document.

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Effects of a 12-week core strength training program on physical fitness and fundamental movement skills in children aged 6–8 years: A randomized controlled trial

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ABSTRACT

This study evaluated the effects of a 12-week core strength training program on physical fitness and fundamental movement skills (FMS) in children aged 6–8 years. A total of 128 primary school children (mean age: 7.01 ± 0.82 years; BMI: 12.78 ± 2.55 kg/m²) were randomly assigned to an experimental group (35 boys, 29 girls) or a control group (33 boys, 31 girls). The experimental group underwent three 40-minute core strength training sessions weekly, while the control group participated in standard physical education classes. Assessments were conducted at baseline and after 12 weeks using the 50-meter sprint, sit-and-reach, and one-minute jump rope tests. FMS were evaluated with backward balance walking and single-leg jumping. Independent samples t-tests compared pre- and post-intervention outcomes, and correlation analyses examined the relationship between core strength, physical fitness, and FMS. The experimental group showed significant improvements over the control group in the 50-meter sprint (-0.57 ± 0.87 s, $p < .05$), single-leg jump (5.86 ± 6.08 s, $p < .01$), side-to-side jump (10.75 ± 12.91 reps, $p < .01$), plank support (26.92 ± 16.86 s, $p < .01$), and back muscle strength (5.28 ± 4.23 kg, $p < .01$). Plank support correlated strongly with back muscle strength ($r = 0.41$, $p < .01$) and inversely with sprint time ($r = -0.47$, $p < .01$). Core strength, lower limb power, coordination, and stability were significantly enhanced in the experimental group, while the control group showed minimal changes. In conclusion, core strength training effectively improves physical fitness and FMS in young children, providing practical guidance for age-appropriate training programs.

Keywords: Physical education, Core strength training, Children, Physical fitness, Fundamental movement skill.

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INTRODUCTION

A lack of adequate physical activity (PA) and exercise can lead to underdeveloped muscle strength in children, negatively impacting their daily activities and sports performance (Masanovic et al., 2024). Developing fundamental movement skills (FMS), in early childhood is important because it has the potential to improve children's ability to successfully participate in games and sports in adolescence and adulthood and helps them retain these skills throughout life (Joschtel et al., 2021). At this stage, children experience rapid development in strength, flexibility, balance, and endurance, which are essential for participating in daily activities and sports (Bull et al., 2020). Physical fitness involves the performance of daily PA or physical exercise (King et al., 2019). Physical fitness, the ability of the human body to effectively and efficiently complete an activity or sport, is widely recognized as an important component of health and a crucial indicator of PA outcomes (Dong et al., 2020). A study involving 212 first-grade children (mean age: 6.95 years) examined gender differences in physical fitness, and found a decline in PA and fitness levels as children transitioned into formal schooling. Boys outperformed girls in endurance and strength tests (e.g., 20-meter run, sit-ups, six-minute run, standing broad jump), while girls excelled in flexibility (Lisowski et al., 2020). Bauer et al. (2022) found that youth who were of normal weight at baseline but became overweight or obese at follow-up exhibited lower academic performance. However, higher cardiorespiratory fitness was shown to potentially counteract the negative effects of excess BMI on academic outcomes. The study suggests that PA programs focusing on both aerobic fitness and motor skills could not only improve physical health but also enhance academic success. Moreover, research examining the relationship between physical fitness and mental health in children and adolescents has found a small to moderate positive association between physical fitness and overall mental well-being (Cadenas-Sanchez et al., 2021). Also, both cardiopulmonary endurance and muscle strength were also positively correlated with self-esteem, self-concept, physical self-perception and well-being, while cardiopulmonary endurance was negatively correlated with depression and muscle strength with anxiety. While speed agility showed a small to moderate positive correlation with self-concept and physical self-perception, and flexibility did not show a correlation with any mental health indicator (Cadenas-Sanchez et al., 2021). A prior study revealed that skill development is enhanced by physical attributes (e.g., fitness, weight status) and psychological attributes (e.g., perceived competence, self-efficacy) (Hulteen et al., 2021).

Fundamental movement skills (FMS) include body movement skills, object manipulation skills and stability control skills. FMS can be classified into three categories: Object control/manipulation skills, such as throwing, catching, dribbling, kicking, hitting, and rolling; Movement skills such as walking, running, jumping, jumping, running, sliding, and jumping; Balance/stability skills such as body roll, bend, dodge, stick balance, one-foot balance, stretch, swing, turn, and twist. These skills are generally recognized as the building blocks of both complex and sport-specific movement skills (Junker et al., 2019; Norup et al., 2023). The FMS acquired in early childhood are essential for future health and the development of more complex movement skills. Children with better FMS are more likely to engage in higher levels of PA, whereas those with poorer movement skills are more likely to adopt a sedentary lifestyle to avoid the challenges associated with PA participation (Graham et al., 2022). Importantly, childhood is a critical period for proficiency in FMS. If children do not receive adequate instruction in movement skills, they may experience developmental delays in proficiency in FMS (Wang et al., 2022). The FMS acquired in early childhood are valuable for future health and the development of complex movement skills.

Core strength, often defined as the capacity of the trunk muscles to stabilize the spine and pelvis during dynamic movements, is increasingly acknowledged as a cornerstone of overall physical function, athletic prowess, and injury prevention (Yilmaz et al., 2022). Moreover, core strength is a fundamental component of

physical fitness in children, playing a crucial role in maintaining posture, balance, and overall movement coordination. It involves the development of the torso muscles responsible for stabilizing and mobilizing the trunk. Developing strong core muscles can enhance sports performance by improving force production in upper and lower extremities (Gong et al., 2024). Moreover, core strength training is beneficial for reducing the risk of sports-related injuries by enhancing musculoskeletal health. Core strength supports children's ability to maintain their position and move effectively. This is vital for developing gross motor skills like running, jumping, climbing, as well as fine motor skills such as writing or drawing. A strong core helps improve posture by preventing slouching or leaning forward while seated. It also enhances balance during various movements (Gong et al., 2024; Chang et al., 2020). A 12-week study by Kumar and Zemková (2022) highlighted the positive impact of core strength training on muscle strength, endurance, and flexibility in school-aged athletes. The study found that core strength training led to significant improvements in abdominal strength, endurance (as measured by the Cooper 12-minute run), and flexibility (assessed via the sit-and-reach test) compared to a control group (Kumar & Zemkova, 2022). Similarly, Lu et al. (2022) investigated the combined effects of SMART goal-setting and 12-week core strength training (CST) on adolescent fitness and exercise attitudes. Results showed that the SMART+CST group outperformed the control group in core endurance and behavioural control. Additionally, the CST group exhibited notable improvements in grip strength, sprint time, long jump performance, and running endurance. These findings underscore the important role of core strength training in improving adolescent fitness, particularly in core endurance, stability, and overall strength (Chang et al., 2020; Kumar & Zemkova, 2022). Another study investigated the effects of a core muscle training (CMT) program on trunk strength and balance in young male soccer players (mean age: 10.8 years). The findings demonstrated significant improvements in trunk flexion and extension strength at both 6 and 12 months. Additionally, performance on the Y Balance Test indicated enhanced dynamic balance. These results underscore the efficacy of CMT in improving core strength and balance among young athletes (Gong et al., 2024).

Therefore, core strength is essential for children's physical fitness and FMS. According to research, core strength training not only increases muscle strength, balance, and flexibility, but it also supports the development of fundamental movement abilities, improves athletic performance, and lowers the risk of sports-related injuries. Furthermore, core strength is linked to physical health and movement skills, allowing youngsters to gain greater control over their body movements and participate in more physical activities. Based on these findings, the present study aimed to investigate the effects of a 12-week core strength training program on physical fitness and FMS scores in children aged 6–8 years. Additionally, the study examined the correlation between core strength and various movement ability indicators, aiming to provide scientific evidence to support physical training programs that promote PA and improve health outcomes in children.

MATERIALS AND METHODS

Participants

A total of 128 primary school students aged 6–8 years (mean age = 7.01 ± 0.82 years, BMI = 12.86 ± 2.25 , 66 boys, 62 girls) were recruited from primary school in Maoming city, Guangdong province, China. Children in good health, without severe chronic diseases or congenital conditions, who voluntarily agreed to participate and provided written consent along with their parents or legal guardians, were included in the study. Participants with prior experience in core strength training or similar programs were excluded. Eligible participants were then randomly assigned to either the control or experimental group using stratified randomization based on gender, age, and body mass index (BMI). Each group comprised 64 students, with the control group consisting of 33 boys and 31 girls, and the experimental group including 35 boys and 29

girls. The study protocol was approved by the Center for Ethics in Human Research, Khon Kaen University (Approval No. HE672147).

Experimental protocol

The experimental group has undergone a 12-week training program (Table 1) consisting of three sessions per week of core strength training and regular physical education classes (Table 2). Each session lasted 40 minutes. This core strength training session have included exercises such as abdominal bracing, abdominal contractions (in the quadruped position), lateral bridges, supine bridges, and lateral trunk rotations on a Swiss ball. Each session has included a 5-minute warm-up (jogging and dynamic stretching), 30 minutes of core training (aerobic, strength, or a combination of both), and a 5-minute cool-down featuring static stretching to promote recovery and reduce muscle stiffness.

The control group has undergone a 12-week physical education training program (Table2), engaging in regular physical exercises for 40 minutes, three times per week, following the standard physical education curriculum. Each session has included a 5-minute warm-up with jogging and dynamic stretching, aimed at increasing muscle flexibility and range of motion, followed by aerobic exercises, strength training, or a combination of both. Each session began with a 5-minute warm-up and ended with a 5-minute cool-down.

Physical fitness tests

1) Fifty-meter sprint

Before the 50-meter sprint, the participants performed a three-minute warm-up. They then sprinted at maximum effort on a straight track. Running times were recorded using a stopwatch (PC80, Shenzhen Tianxing Electronics Co., Ltd., China) with an accuracy of 0.1 seconds.

Table 1. Core strength training program.

Week	Training content	Sets	Reps/ Duration	Intervals
1-2	Forward/Backward Jumps, Left/Right Jumps, Hip Flexion Abduction Jumps, Arms Knees Jumps, Contralateral Elbow-Knee Pad Jumps, Supine Alternating Heel Contact, Supine Hip Raise, Left/Right Bent Knee Lateral Support	2	8-10 reps	60 s
3-4	Forward/Backward Jumps, Left/Right Jumps, Hip Flexion Abduction Jumps, Arms & Knees Jumps, Contralateral Elbow-Knee Pad Jumps, Supine Alternating Heel Contact, Supine Hip Raise, Left/Right Bent Knee Lateral Support	2	10-12 reps	50 s
5-6	Reverse Curls, Lateral Leg Curls, Supine Core Curls, Side Plank, Push-ups & Abdominal Jumps, Swiss Ball Incline Bridge Lift, Swiss Ball Supinated Alternating Forward Knee Lift, Swiss Ball Overhead Stooping Bridge Leg Raise, Swiss Ball Opposite Side Alternating Hand & Foot Raises	2	8-12 reps	45 s
7-8	Reverse Curls, Lateral Leg Curls, Supine Core Curls, Side Plank, Push-ups & Abdominal Jumps, Swiss Ball Incline Bridge Lift, Swiss Ball Supinated Alternating Forward Knee Lift, Swiss Ball Overhead Stooping Bridge Leg Raise, Swiss Ball Opposite Side Alternating Hand & Foot Raises	2	12 reps	45 s
9-10	Swiss Ball Incline Plank Support Toe Brace, Swiss Ball Supine Dynamic Hip Bridge, Swiss Ball Downward Sloping Push-up with Bent Knees, Swiss Ball Supine Straight Leg Hip Lift, Swiss Ball Upper Incline Alternating Shoulder Turns, Swiss Ball Supine Leg Raise, Swiss Ball Overhead "Y", Swiss Ball Supine Ball Curl, Swiss Ball Downward Slanting Overhead Bridge Alternating Leg Lifts, Swiss Ball Supine Leg Curl	2	10-12 reps/ 40-60 s	45 s
11-12	Swiss Ball Incline Plank Support Toe Brace, Swiss Ball Supine Dynamic Hip Bridge, Swiss Ball Downward Sloping Push-up with Bent Knees, Swiss Ball Supine Straight Leg Hip Lift, Swiss Ball Upper Incline Alternating Shoulder Turns, Swiss Ball Supine Leg Raise, Swiss Ball Overhead "Y", Swiss Ball Supine Ball Curl, Swiss Ball Downward Slanting Overhead Bridge Alternating Leg Lifts, Swiss Ball Supine Leg Curl	2	12 reps/ 45-60 s	45 s

Table 2. Regular physical education program.

Week	Training Content	Sets	Reps/Time	Intervals
1-2	30m sprint practice	2	2 laps	60 s
	Basketball passing & catching	5	10 reps	60 s
3-4	30m running exercise	3	2 laps	60 s
	Basketball dribbling	4	5×15m	30 s
5-6	Standing long jump	2	5 reps	30 s
	Basketball shooting	5	10 reps	30 s
7-8	Standing long jump	3	5 reps	30 s
	Soccer passing & catching	5	12×3 m	60 s
9-10	Rope skipping	2	1 min/session	60 s
	Soccer dribbling	4	3×25 m	45 s
11-12	Rope skipping	3	1 min/session	60 s
	Soccer shooting	4	5 reps	30 s

2) Sit-and-reach test

The flexibility test was conducted using an electronic sit-and-reach tester (Model HWD21-1231, Li Ning Co., Ltd., China), which has a measurement range of 60 cm and a resolution of 0.1 cm. Participants were instructed to sit barefoot with their knees fully extended and their heels positioned firmly against the footplate of the device, maintaining a distance of 10–15 cm between the feet. They then leaned forward gradually, using their middle fingers to push a sliding cursor. The best performance from two trials was recorded. The results were measured in centimetres.

3) One-minute jump rope

A counter-equipped jump rope (Li Ning Co., Ltd., China) with a standard base length of 2.8 meters was utilized for the test. Participants adjusted the rope length by raising the handles to chest level to ensure proper fit. They were instructed to perform as many jumps as possible within 1 minute, only successful jumps were counted. The built-in counter automatically recorded the total number of completed jumps (times).

Fundamental movement skill test

1) Backward balance walking test

This test was designed to assess balance and coordination. Participants were instructed to walk backward three times on three balance beams, each 3 meters in length, with widths of 6 cm, 4.5 cm, and 3 cm, respectively. The total number of steps taken across all attempts was recorded. The measurement unit used was steps.

2) Lateral movement test

Participants were asked to stand on two wooden platforms (25 cm × 25 cm × 5.7 cm) and moved them alternately as fast as possible within 20 seconds. Two trials (one for each leading leg) were conducted, and the total number of completed movements (times) was recorded.

3) Single-leg jump test

This test evaluated leg coordination, strength, and dynamic stability. Participants performed a single-leg jump over a 25 cm-high mat following a short run-up. Scores were assigned based on performance (3 points for a successful first attempt, 2 points for the second, and 1 point for the third). The measurement unit of this test is centimetres (cm.).

4) Side-to-side jump test

Participants were instructed to perform lateral jumps over a wooden bar (60 cm × 4 cm × 2 cm) as many times as possible within a 15-second interval. Each participant completed two attempts, and the total number of successful jumps was recorded. The results were measured in counts (times).

Core strength and flexibility tests

1) Sit-ups test

Participants lay on their backs with knees bent, feet secured, and arms crossed over their chests. They were instructed to perform as many sit-ups as possible within one minute, with only properly executed repetitions being counted. The results were recorded as the number of repetitions, measured in counts (times).

2) Plank support test

Participants were instructed to maintain a plank position with their elbows positioned 30 cm apart, while keeping both the shoulders and hips elevated approximately 25 cm above the floor. Timing began at the command "begin" and ended when any part of the body made contact with the mat. The duration held was recorded in seconds (s).

3) Back muscle strength test

The back strength test was conducted using an electronic back strength meter (BCS-400, HFD Tech Co., Beijing, China). Participants were instructed to pull the handle with maximum effort while keeping their legs straight and avoiding any backward bending of the torso. Back strength was measured in kilograms (kg).

4) One-legged stand test

Participants were instructed to stand on their non-dominant leg with their hands placed on their hips and their eyes fixed on a designated point on the wall. The duration for which balance was maintained was recorded in seconds (s) to assess static balance.

Statistical analysis

All data were analysed using SPSS version 28.0 (IBM Corp., Armonk, NY, USA) to determine statistical significance. Descriptive statistics, including means and standard deviations, were calculated for all variables both before and after the intervention. To examine the effects of core strength training, independent sample t-tests were used to compare post-intervention outcomes between experimental and control groups. If the assumption of normality was violated, non-parametric tests, such as the Mann-Whitney U test, were applied for between-group comparisons. Additionally, Pearson's correlation coefficient was calculated to assess the relationships between variables, such as the link between improvements in core strength and physical performance measures. The significance level was set at $p < .05$, and effect sizes (Cohen's d) were computed to quantify the magnitude of differences between groups. All analyses were conducted with a significance threshold of $\alpha = .05$.

RESULTS

The baseline characteristic of the participants

Table 3 shows, before the intervention, the experimental group (EG) and control group (CG) exhibited some differences in height, weight, BMI, and physical fitness tests (50-meter dash, sit and reach, 1-minute rope skipping). Overall, the EG tended to have higher values in height, weight, and BMI compared to the CG. This difference was particularly significant within the 6-year-old subgroup, where the EG showed notably greater height and weight than the CG. Regarding physical fitness tests, the EG performed slightly better in the 50-

meter dash and 1-minute rope skipping, especially among the 6-year-olds. However, these differences were not statistically significant, and the overall disparities were relatively small. This suggests that, prior to the experiment, the physical fitness levels of both groups were comparable, with some expected individual variation.

Table 3. The baseline characteristic of the participants.

Age (year)	Group	n	Height (cm)	Weight (kg)	BMI (kg/m ²)
6	CG	20	116.59 ± 4.49	15.37 ± 2.87	11.23 ± 1.39
	EG	22	121.82 ± 4.28	18.81 ± 3.43	12.59 ± 1.68
7	CG	23	124.99 ± 5.59	20.05 ± 4.95	12.71 ± 2.21
	EG	20	125.29 ± 5.30	20.24 ± 4.16	12.80 ± 1.72
8	CG	21	129.51 ± 7.50	24.37 ± 7.32	14.32 ± 2.89
	EG	22	131.10 ± 6.29	23.21 ± 4.88	13.45 ± 2.28
Total	CG	64	123.85 ± 7.92	20.01 ± 6.42	12.78 ± 2.55
	EG	64	126.09 ± 6.56	20.77 ± 4.54	12.95 ± 1.93
Age (year)	Group	n	Fifty Meter Sprint (s)	Sit-and-Reach Flexibility (cm)	1-Minute Jump Rope (reps)
6	CG	20	12.05 ± 1.00	5.17 ± 4.18	27.80 ± 12.19
	EG	22	11.99 ± 1.01	5.47 ± 4.47	28.55 ± 17.59
7	CG	23	11.41 ± 1.05	6.38 ± 3.96	34.65 ± 14.21
	EG	20	11.15 ± 1.11	6.57 ± 5.09	37.10 ± 16.15
8	CG	21	11.41 ± 1.26	8.17 ± 6.37	43.90 ± 19.48
	EG	22	11.31 ± 1.19	8.58 ± 4.13	43.95 ± 20.68
Total	CG	64	11.61 ± 1.13	6.59 ± 5.02	35.55 ± 16.69
	EG	64	11.50 ± 1.15	6.88 ± 4.68	36.52 ± 19.13

Note. No statistically significant differences were found between groups across all variables ($p > .05$).

Comparison of each index between control group and experimental group in pre-test

Data analysis of Table 4 revealed minimal baseline differences between the CG and EG across various physical fitness tests, with most differences not reaching statistical significance ($p > .05$). Specifically, in the 50-meter sprint, the CG averaged 11.61 ± 1.13 seconds and the EG 11.50 ± 1.15 seconds ($p = .38$), indicating no significant difference in sprint performance. In the sit-and-reach test, scores were 6.59 ± 5.02 cm for the CG and 6.88 ± 4.68 cm for the EG ($p = .73$), showing comparable flexibility. Similarly, the one-minute jump rope test results were 35.55 ± 16.69 repetitions for the CG and 36.52 ± 19.13 repetitions for the EG ($p = .64$), with no significant difference in aerobic endurance and coordination. Other measures, including backward balance walk, lateral movement, single-leg jump, side-to-side jump, sit-ups, plank support, back muscle strength, and one-legged stance, all showed p -values $> .05$, confirming no statistically significant differences between groups. These findings indicate that the baseline physical fitness and motor skills of both groups were highly similar before the intervention, validating the comparability of groups and providing a solid foundation for assessing the effects of the 12-week core strength training program.

Comparison of each index between control group and experimental group in post-test

Table 5 compared the physical performance and FMS of the CG and the EG to analyse their differences. The results indicate that EG outperformed CG in most tests, with significant differences observed in the 50-meter sprint, single-leg jump, side-to-side jump, plank support, and back muscle strength tests ($p < .05$). The effect sizes (Cohen's d) ranged from moderate to large, demonstrating EG's clear advantage in these aspects. Specifically, EG performed better in the 50-meter sprint, with a p -value of .019 and a moderate effect size ($d = 0.37$), indicating a significant difference. In the single-leg jump test, EG showed superior explosive power ($p = .006$, $d = -0.51$), and the side-to-side jump test also highlighted EG's advantage ($p = .008$, $d = -0.44$). The most notable differences were found in the plank support and back muscle strength tests, where

EG showed remarkable superiority ($p < .01$ and $p = .005$, respectively), with large effect sizes ($d = -0.73$ and $d = -0.6$), emphasizing EG's dominance in core stability and back strength.

Although CG showed slightly weaker performance in some tests, not all differences were statistically significant. For example, in the sit-and-reach and backward balance walking tests, the differences between CG and EG were not significant ($p > .05$), with small effect sizes ($d = -0.27$ and $d = -0.36$), suggesting minimal differences in flexibility and balance. However, in the jump rope and sit-up tests, CG still underperformed compared to EG, with p -values of .009 and .043 and moderate effect sizes ($d = -0.43$ and $d = -0.37$), indicating EG's superiority in endurance and core strength. Overall, EG demonstrated a higher level of physical fitness across multiple tests, particularly in explosive power, endurance, and core strength. CG exhibited weaker performance in most areas, suggesting possible deficiencies in training, strength, and endurance.

Table 4. Comparison of pre-test measured outcomes between control and experimental groups.

Test	CG (Mean $\pm$ SD)	EG (Mean $\pm$ SD)	p	95% CI of CG		95% CI of EG		Cohen's d
				Lower Bound	Upper Bound	Lower Bound	Upper Bound	
50-meter sprint (s)	11.61 $\pm$ 1.13	11.50 $\pm$ 1.15	.38	11.3304	11.8949	11.2089	11.7814	-0.09
Sit-and-reach (cm)	6.59 $\pm$ 5.02	6.88 $\pm$ 4.68	.73	5.335	7.84	5.715	8.054	-0.07
1minute jump rope (rep)	35.55 $\pm$ 16.69	36.52 $\pm$ 19.13	.64	31.38	39.72	31.74	41.29	-0.06
Backward balance walking test (step)	42.78 $\pm$ 15.11	43.41 $\pm$ 14.57	.88	39.01	46.56	39.77	47.05	-0.04
Lateral movement test (rep)	15.03 $\pm$ 3.38	15.30 $\pm$ 3.34	.66	14.19	15.88	14.46	16.13	-0.08
Single leg jump Test (cm)	51.17 $\pm$ 7.75	52.66 $\pm$ 8.07	.30	49.24	53.11	50.64	54.67	-0.19
Side-to-side jump test (rep)	37.63 $\pm$ 11.09	39.30 $\pm$ 11.93	.41	34.86	40.39	36.32	42.28	-0.14
Sit-ups test (rep)	23.63 $\pm$ 8.85	23.70 $\pm$ 8.90	.96	21.41	25.84	21.48	25.93	-0.01
Plank support (s)	54.86 $\pm$ 16.65	56.13 $\pm$ 14.26	.94	50.7	59.02	52.56	59.69	-0.08
Back muscle strength (kg)	19.14 $\pm$ 7.18	20.05 $\pm$ 7.27	.56	17.35	20.93	18.23	21.86	-0.14
One legged stand (s)	48.23 $\pm$ 26.87	49.09 $\pm$ 25.57	.75	41.52	54.94	42.71	55.48	-0.03

Note. CG = Control group, EG = Experimental group. Sit-and-reach, Lateral movement test, Side-to-side jump test were tested by means independent sample t -test. 50-meter sprint, 1minute jump rope, Backward balance walking test, Single leg jump test, Sit-ups test, Plank support, Back muscle strength, One legged stand were tested using non-parametric test (Mann-Whitney U -test).

Comparison of physical fitness between experimental and control groups before and after intervention

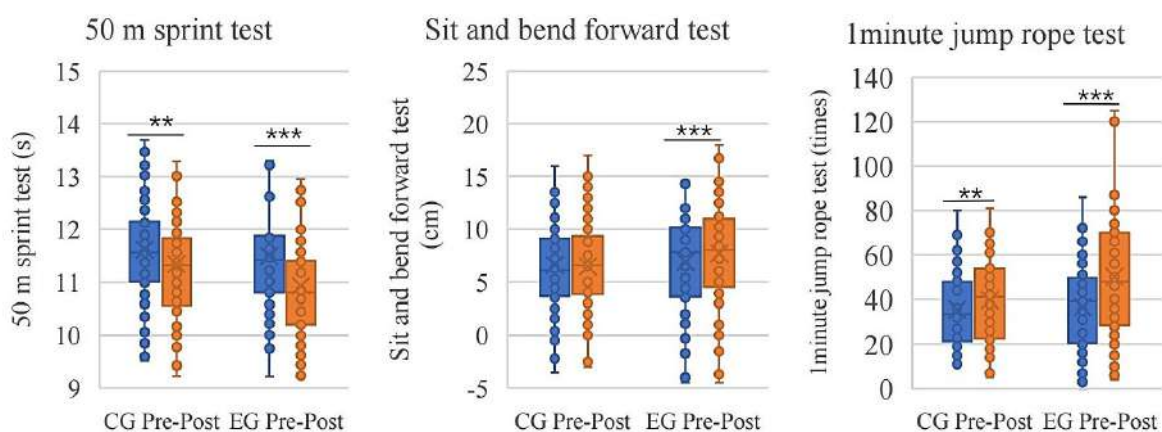
Figure 1 illustrates the performance changes in the experimental group (EG) and control group (CG) before and after 12 weeks of core strength training in the 50-meter sprint, sit-and-reach test, and one-minute jump rope test. Overall, the EG demonstrated significant improvements in speed and endurance, while flexibility showed minimal change. In contrast, the CG exhibited only minor overall changes. In the 50-meter sprint test, the running time of the EG was significantly reduced after training, leading to a notable improvement in sprint speed, which reached statistical significance ($p < .05$). This finding indicates that core strength training is effective in enhancing sprint performance. Meanwhile, the CG showed little change in performance, suggesting that sprint speed did not improve significantly without training. In the sit-and-reach test, both the EG and CG showed slight improvements in flexibility; however, the differences were not statistically significant ($p > .05$). This suggests that core strength training has a limited effect on flexibility, and specialized stretching exercises may be required to achieve substantial improvements in this parameter. In the one-

minute jump rope test, the number of repetitions performed by the EG increased significantly post-training, demonstrating a highly significant improvement ($p < .01$). This indicates that core strength training effectively enhances endurance, coordination, and lower limb muscular endurance. In contrast, the CG's performance showed no significant change, suggesting that physical fitness does not improve substantially without training intervention. In summary, 12 weeks of core strength training significantly improved sprint speed and jump rope endurance in the EG but had minimal impact on flexibility. The CG exhibited negligible changes, reinforcing the role of core training in enhancing athletic performance, particularly in speed and endurance development.

Table 5. Comparison of each index between control group and experimental group in post-test.

Test	CG (Mean $\pm$ SD)	EG (Mean $\pm$ SD)	<i>p</i>	95% CI of CG		95% CI of EG		Cohen's <i>d</i>
				Lower Bound	Upper Bound	Lower Bound	Upper Bound	
50-meter sprint (s)	11.34 $\pm$ 1.07	10.93 $\pm$ 1.19	.01	11.0712	11.6152	10.6306	11.2329	0.37
Sit-and-reach (cm)	6.46 $\pm$ 4.59	7.67 $\pm$ 4.76	.15	5.282	7.613	6.435	8.848	-0.27
1minute jump rope (rep)	39.70 $\pm$ 17.98	50.23 $\pm$ 26.15	.009	35.22	44.34	43.66	56.94	-0.43
Backward balance walking test (step)	44.72 $\pm$ 15.27	50.39 $\pm$ 14.34	.07	41.59	48.99	47.18	54.31	-0.36
Lateral movement test (rep)	15.63 $\pm$ 3.64	17.36 $\pm$ 4.69	.04	14.73	16.57	16.27	18.62	-0.4
Single leg jump Test (cm)	53.75 $\pm$ 8.26	58.52 $\pm$ 9.46	.006	51.72	55.9	56.02	60.8	-0.51
Side-to-side jump test (rep)	44.64 $\pm$ 10.34	50.05 $\pm$ 12.22	.008	42.08	47.32	46.9	53.1	-0.44
Sit-ups test (rep)	24.92 $\pm$ 7.96	27.83 $\pm$ 8.16	.04	22.87	26.91	25.75	29.9	-0.37
Plank support (s)	68.78 $\pm$ 19.01	83.05 $\pm$ 19.13	<.01	63.92	73.57	78.72	88.26	-0.73
Back muscle strength (kg)	21.11 $\pm$ 6.71	25.33 $\pm$ 8.44	.005	19.53	22.91	23.28	27.55	-0.6
One legged stand (s)	64.05 $\pm$ 30.84	75.72 $\pm$ 32.79	.04	56.54	72.15	67.3	83.94	-0.39

Note: CG = Control group, EG = Experimental group. Sit-and-reach, 1-minute jump rope test, Side-to-side jump test, and sit-up test were tested by independent sample t-test. 50-meter sprint, Backward balance walking test(step), Lateral movement test, Single leg jump test, Plank support, Back muscle strength, One legged stand were tested using non-parametric test (Mann-Whitney U-test).

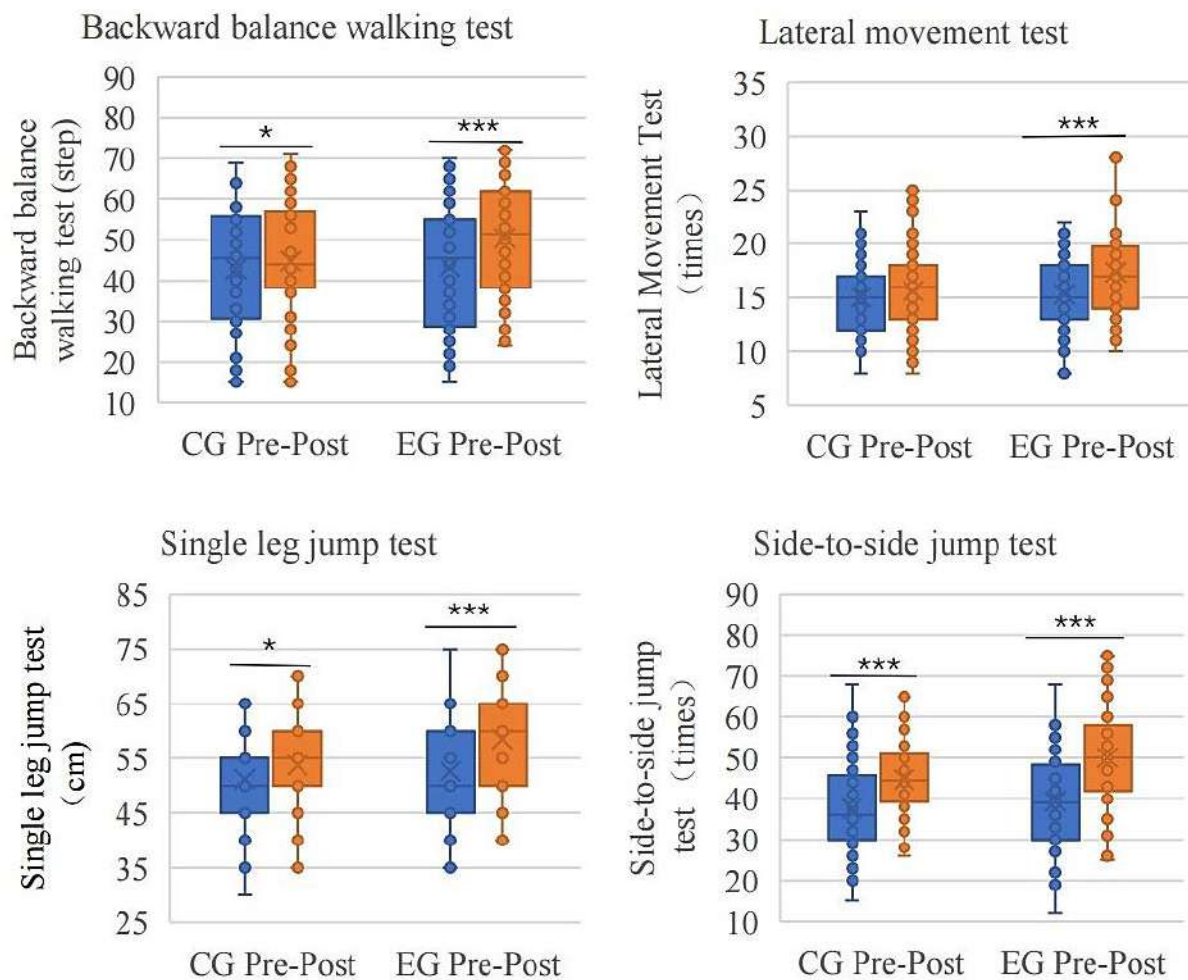


Note: EG = Experimental group, CG = Control group; Pre = pre-test, Post = Post-test. * Indicates that the significance level is $p < .05$. ** Indicates that the significance level is $p < .01$.

Figure 1. Comparison of physical fitness between experimental and control groups before and after intervention.

Comparison of FMS between experimental and control groups before and after intervention

Figure 2 illustrates that after 12 weeks of core strength training, the experimental group (EG) demonstrated significant improvements across multiple fitness tests, particularly in lower limb explosiveness, coordination, and endurance. Specifically, in the Lateral Movement Test, the EG showed a statistically significant improvement ($p < .05$), indicating that core strength training enhances flexibility and lateral movement ability. In the Single-Leg Jump Test, the EG's performance improved significantly, reaching a highly significant level ($p < .01$), suggesting that core training effectively enhances lower limb explosive power and stability. Additionally, in the Side-to-Side Jump Test, the EG exhibited a statistically significant improvement post-training ($p < .01$), further reinforcing the crucial role of core strength training in enhancing lower limb endurance and coordination. However, in the Backward Balance Walking Test, neither the EG nor the CG demonstrated significant changes, suggesting that core training alone has a limited effect on balance, and additional balance-specific training may be necessary to achieve further improvements. In contrast, the CG showed minimal changes across all tests, indicating that individuals who did not undergo core strength training experienced limited progress in physical fitness. These findings suggest that core strength training not only enhances athletic performance—particularly lower limb endurance, explosiveness, and coordination—but also serves as a foundation for further improvements in balance and other motor skills.

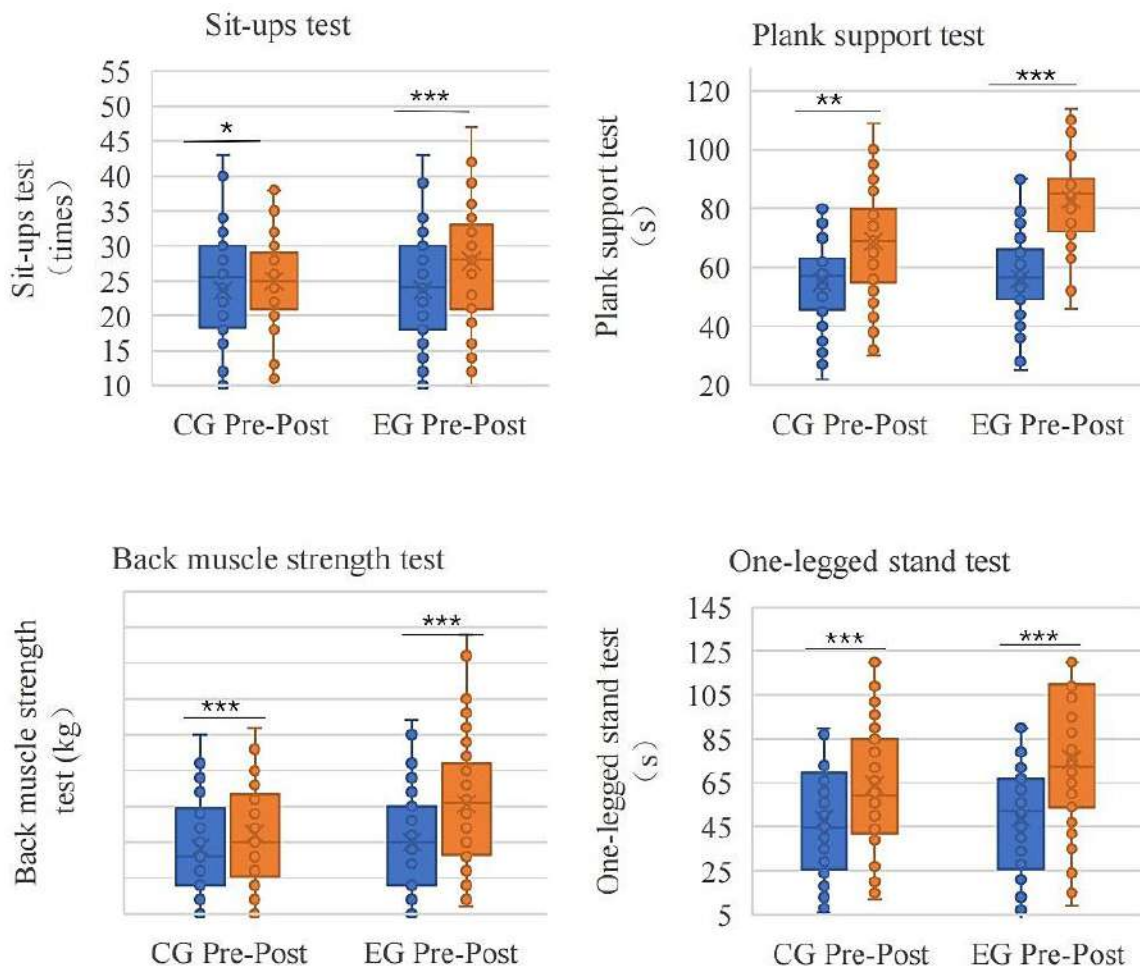


Note: EG = Experimental group, CG = Control group; Pre = pre-test, Post = Post-test. * Indicates that the significance level is $p < .05$. ** Indicates that the significance level is $p < .01$.

Figure 2. Comparison of FMS between experimental and control groups before and after intervention.

Comparison of core strength between experimental and control groups before and after intervention

Figure 3 illustrates the effects of core training on physical fitness by comparing the performance of the EG and the CG before and after 12 weeks of core strength training. The results of the sit-up test show that the experimental group increased the number of repetitions after the training, while the control group showed no significant change. The plank test revealed a significant improvement in the experimental group's support time, indicating enhanced core muscle endurance, whereas the control group showed minimal change. In the back muscle strength test, grip strength increased in the experimental group, suggesting that core training improved back muscle strength, while the control group exhibited no change. Furthermore, in the one-leg standing test, the experimental group showed a significant improvement in balance, with increased time spent standing on one leg, whereas the control group showed little to no improvement. These findings suggest that systematic core training not only enhances muscle endurance and strength but also improves physical balance, which can positively impact athletic performance and daily activities.



Note: EG = Experimental group, CG = Control group; Pre = pre-test, Post = Post-test. * Indicates that the significance level is $p < .05$. ** Indicates that the significance level is $p < .01$.

Figure 3. Comparison of core strength between experimental and control groups before and after intervention.

Correlation between core strength and physical fitness

Table 6 shows that plank support is positively correlated with back muscle strength, one-legged stance, and 1-minute jump rope, with a particularly strong correlation with back muscle strength ($r = 0.412$) and a

significant negative correlation with the 50-meter sprint ($r = -0.477$). This suggests that individuals with greater core muscular endurance tend to have stronger back muscles and improved sprint performance (as a shorter sprint time indicates better performance). Back muscle strength is significantly correlated with one-legged stance, sit-and-reach, and 1-minute jump rope ($p < .05$), indicating that back strength plays a role in balance, flexibility, and aerobic capacity. One-legged stance is significantly correlated with plank support, back muscle strength, and 1-minute jump rope ($p < .05$), reinforcing the critical role of core strength in maintaining balance. The 50-meter sprint is negatively correlated with core-related abilities such as sit-ups, plank support, back muscle strength, one-legged stance, and 1-minute jump rope, indicating that greater core strength is associated with faster sprint times (i.e., shorter times). The sit-and-reach test is significantly correlated with back muscle strength and 1-minute jump rope, suggesting that flexibility may be related to muscular strength and endurance but does not have a significant relationship with sprint performance. The 1-minute jump rope test shows a significant positive correlation with most core strength indicators (sit-ups, plank support, back muscle strength, and one-legged stance), indicating that jump rope is not only a measure of cardiorespiratory endurance but also closely linked to core strength. Core muscles (as assessed by sit-ups, plank support, and back muscle strength) have a significant impact on sprint performance, balance, jumping ability, and flexibility. Sprint performance (50-meter sprint) is negatively correlated with core strength, suggesting that a stronger core contributes to better sprint results. The 1-minute jump rope test is associated with multiple physical fitness indicators, making it a potentially effective measure of overall fitness. Flexibility (sit-and-reach) is linked to back strength and aerobic capacity but has no significant correlation with sprint performance.

Table 6. Correlation between core strength and physical fitness.

	Sit-ups	Plank support	Back muscle strength	One legged stand	Fifty meter sprint	Sit and reach	One minute jump rope
Sit-ups	1						
Plank support	.258**	1					
Back muscle strength	.324**	.412**	1				
One legged stand	.141	.385**	.221*	1			
Fifty meter sprint	-.365**	-.477**	-.408**	-.415**	1		
Sit-and-reach	.196*	.212*	.360**	.129	-.154	1	
One minute jump rope	.260**	.316**	.405**	.319**	-.382**	.303**	1

Note. ** Correlation is significant at the .01 level (2-tailed). * Correlation is significant at the .05 level (2-tailed).

Correlation between core strength and FMS

Table 7 shows that core strength metrics, such as sit-ups, plank support, and back muscle strength, are highly correlated with each other (Plank Support & Back Muscle Strength: $r = 0.55$), indicating a close relationship between different aspects of core stability (dynamic and static support, muscular strength). Core Strength and Balance Ability: One-legged stance is significantly correlated with all core strength indicators (Sit-ups: $r = 0.29$, Plank Support: $r = 0.45$, Back Muscle Strength: $r = 0.34$), suggesting that a stronger core helps in maintaining static balance. Backward balance walk is associated with plank support ($r = 0.44$), one-legged stance ($r = 0.33$), and side-to-side jump ($r = 0.26$), indicating that core stability plays an essential role in dynamic balance. Core Strength and Dynamic Movement Skills: Lateral movement is significantly correlated with core strength (Sit-ups: $r = 0.29$, Plank Support: $r = 0.42$, Back Muscle Strength: $r = 0.41$), suggesting that greater core stability enhances lateral mobility. Single-leg jump is strongly correlated with core strength (Sit-ups: $r = 0.341$, Plank Support: $r = 0.52$, Back Muscle Strength: $r = 0.50$), highlighting the importance of core engagement in single-leg explosive movements. Side-to-side jump is also significantly related to core strength (Sit-ups: $r = 0.36$, Plank Support: $r = 0.28$, Back Muscle Strength: $r = 0.44$), demonstrating that core strength positively influences agility and lateral jumping ability. Core strength plays a vital role in both static balance (one-legged stance, backward balance walks) and dynamic movement skills.

(lateral movement, single-leg jump, side-to-side jump). The stronger the core, the better the balance, agility, and jumping performance, reinforcing the importance of core training for athletic performance. Back muscle strength and plank support appear to be the most influential factors affecting multiple movement skills, suggesting that core stability and back strength are crucial for overall movement efficiency.

Table 7. Correlation between core strength and FMS.

	Sit-ups	Plank support	Back muscle strength	One legged stand	Backward balance walking	Lateral movement	Single leg jump	Side-to-side jump
Sit-ups	1							
Plank support	.18	1						
Back muscle strength	.39**	.55**	1					
One legged stand	.29*	.45**	.34**	1				
Backward balance walking	.23	.44**	.21	.33**	1			
Lateral movement	.29*	.42**	.41**	.33**	.09	1		
Single leg jump	.34**	.52**	.50**	.37**	.16	.30*	1	
Side-to-side jump	.36**	.28*	.44**	.43**	.26*	.34**	.43**	1

Note. ** Correlation is significant at the .01 level (2-tailed). * Correlation is significant at the .05 level (2-tailed).

DISCUSSION

This study aimed to evaluate the effects of a 12-week core strength training program on physical fitness and FMS in children aged 6 to 8 years. Specifically, it examined whether such training could lead to improvements in speed, explosive power, endurance, coordination, and core stability. The results indicate that core strength training not only enhances core muscle endurance and strength but also contributes to significant improvements in various components of physical fitness, including sprint performance, cardiovascular endurance, and lower limb explosive power. Moreover, a strong correlation was observed between core strength, physical fitness, and FMS, emphasizing the critical role of core stability in overall athletic performance and motor skill development.

In tests pertaining to the core, such as the plank support and sit-up tests, the experimental group demonstrated notable gains, suggesting that the core strength training program effectively increased the endurance and strength of the core muscles. These results are in line with earlier studies, the trunk muscular endurance test (dynamic curl-up, static curl-up, plank, and lateral plank), the single-leg balancing test, and the functional mobility screen were used to assess the children both before and after the intervention. When measured by FMS scores at the end of the session, the experiment group demonstrated a significant improvement in trunk muscular endurance, flexibility, balance, and movement capability (Chang et al., 2020; Kumar & Zemkova, 2022; Lu et al., 2022). Research has shown that core strength training enhances muscle endurance, balance, and overall physical performance. The EG showed significant improvements in the 50-meter sprint and one-minute jump rope tests, indicating that core strength training contributes to enhanced speed and endurance. After a 12-week intervention, both the core strength and weight training groups showed significant improvements in abdominal strength (sit-ups: 18.70 ± 3.20 to 22.21 ± 3.50 ; 17.60 ± 3.29 to 21.60 ± 3.63), endurance (12-min run: 1817 ± 185.78 m to 2008.97 ± 214.79 m; 1806 ± 237.25 m to 2002.59 ± 83.32 m), and flexibility (sit and reach: 23.48 ± 2.75 cm to 25.96 ± 2.38 cm; 23.66 ± 2.92 cm to 25.86 ± 2.55 cm). In contrast, the control group showed declines in all areas. The weight training group improved slightly more in strength and endurance, while the core training group saw greater gains in flexibility (Kumar & Zemkova, 2022). The EG demonstrated significant improvements in the single-leg jump and lateral jump tests, supporting the findings of Chang et al. (2020), who noted that core strength training enhances both muscular endurance and motor coordination. Similarly, another study found that core stability training

significantly improved balance in young male basketball players, emphasizing the role of core strength in dynamic movements that require rapid changes in direction and jumping (Gong et al., 2024). These improvements were also evident in the experimental group, further supporting the positive impact of core strength training on children's motor skills. The CG which did not undergo core strength training, showed minimal improvements, highlighting the importance of targeted core training for enhancing physical fitness. This lack of significant change in the CG suggests that regular physical education classes alone may not be sufficient to improve core strength and related fitness components. The scores were significantly different in both groups before and after the single-leg standing with eyes closed test. In the star excursion balance test, the experimental group showed a significant difference or highly significant difference with an average effect size of when the left or right foot supported in the other directions before and after the training (Junker & Stoggl, 2019).

The experimental group (EG) exhibited significant improvements in FMS, particularly in tests assessing lower limb explosiveness, coordination, and lateral movement. For example, the single-leg jump and side-to-side jump tests showed highly significant improvements, indicating that core strength training enhances lower limb explosive power and agility. These findings are consistent with the work of Hulteen et al. (2018), who emphasized the importance of core stability in the development of foundational movement skills. However, the backward balance walking test did not show significant improvements in either group, suggesting that core strength training alone may not be sufficient to enhance balance. This finding aligns with the study by Junker and Stoggl (2019) which concluded that while core training improves muscle performance, additional balance-specific exercises may be necessary to achieve significant improvements in balance. A study by Kumar and Zemkova (2022)¹⁷ found that 12 weeks of core strength training significantly improved muscle strength, endurance, and flexibility in school-aged athletes. The intervention group, both core strengthening and weight training programs were effective in improving abdominal strength. Significantly increase endurance. Significantly enhance flexibility. Their findings align with those of the current study, indicating that core strength training not only enhanced core muscle endurance but also improved overall physical performance, particularly in endurance and strength. They also noted that core strength training had a significant effect on improving athletes' explosive power and flexibility, which corresponds with the significant improvements observed in the experimental group in the 50-meter sprint and jump rope tests. Marani et al. (2020) showed that core stability training enhanced the posture and propulsion efficiency of teenage swimmers while also considerably increasing their core muscular strength. Their results further confirm the beneficial effects of core strength training on children's physical fitness and performance, as evidenced by the experimental group's notable gains in the plank and back muscular strength tests. The study discovered that junior swimmers' core muscle strength increased when they used a Swiss ball for core stability exercises (Kumar & Zemkova, 2022).

The correlation analysis revealed strong relationships between core strength and various physical fitness indicators. Plank support, a measure of core endurance, was positively correlated with back muscle strength, one-legged stance, and the one-minute jump rope test, indicating that individuals with greater core endurance tend to have stronger back muscles and better balance. Additionally, the 50-meter sprint was negatively correlated with core strength, suggesting that a stronger core contributes to faster sprint times. These findings are consistent with the previous work (Marani et al., 2020) who reported that core stability exercises improved swimming performance by enhancing body position and propulsion efficiency. The experimental group's posttest score of 7.5 was higher than the control group's score of 2.24. It means that junior swimmers can strengthen their core muscles by performing core stability workouts using a Swiss ball. Core strength was also significantly correlated with FMS, particularly in tests assessing dynamic movement skills, such as lateral movement, single-leg jumps, and side-to-side jumps. This suggests that core stability plays a crucial role in

enhancing agility, coordination, and explosive power. The strong correlation between core strength and FMS supports the model proposed by Hulteen et al. (2018), which posits that motor skills develop in conjunction with physical fitness and perceived competence. A study by Chang et al. (2020) showed that a six-week core strength training program significantly improved the physical fitness, motor skills, and balance abilities of school-aged children. Their findings align with the results of the current study, suggesting that core strength training can effectively enhance children's physical performance, particularly in balance and motor coordination. After the intervention, the experiment group showed significant improvement in trunk muscular endurance, movement capability (FMS scores), flexibility, and balance. Additionally, the experiment group outperformed the control group in all outcome measures. Chang et al. (2020) also noted that core strength training not only improved children's muscular endurance but also enhanced their motor coordination, which aligns with the significant improvements observed in the experimental group in the single-leg jump and lateral jump tests in the current study. The experiment group showed significant improvements in all outcomes, with moderate to high effect sizes, especially in muscular fitness, FMS scores, and balance (Cohen's $d = 0.79-1.3$). In contrast, the GPE group exhibited only minor improvements, with increases in side plank, FMS scores, and flexibility but decreases in static curl-up and plank performance. Overall, the experiment group program outperformed in all measured domains. These results align with previous research highlighting the role of core stability training in enhancing balance and dynamic movement, particularly for athletes (Marani et al., 2020). Their study emphasized the importance of core strength in dynamic movements, especially in sports requiring rapid direction changes and jumping. After ten weeks of experimental intervention, traditional strength training and core stability training had differing effects on the rise of scores in static balance ability assessments. Significant gains were observed in single-leg standing with eyes test scores for both groups. After 10 weeks of core stability training demonstrated substantial improvements in prone, supine, and left lateral positions, as well as a significant improvement in left lateral position. This is consistent with the significant improvements observed in the experimental group in the lateral movement and single-leg jump tests, further supporting the positive impact of core strength training on children's motor skills. The results of this study have important implications for physical education and training programs aimed at children. Incorporating core strength training into regular physical education curricula could significantly enhance children's physical fitness and motor skill development. Given the strong correlation between core strength and various aspects of physical fitness, such as sprinting, jumping, and endurance, core training should be considered a fundamental component of any physical education program. Moreover, the findings suggest that core strength training can be particularly beneficial for children who are at risk of physical inactivity or who have underdeveloped motor skills. By improving core stability, children may be more likely to engage in physical activities, thereby reducing the risk of chronic diseases such as obesity and cardiovascular disease.

This study is the first to systematically examine the effects of 12 weeks of core strength training on physical fitness and FMS in children aged 6-8 years. The study provides valuable insights into how core strength training enhances multiple aspects of physical fitness, including speed, endurance, explosive power, coordination, and core stability. Additionally, the research utilized a well-designed randomized controlled trial (RCT) with a clear intervention protocol, ensuring high internal validity. By including a range of physical tests (e.g., 50-meter sprint, sit-and-reach, one-minute jump rope) and FMS (e.g., single-leg jump, side-to-side jump), the study offers a comprehensive assessment of children's physical development. The study's findings contribute not only to the academic understanding of core strength training in early childhood but also have practical implications for the design of physical education programs aimed at improving children's overall fitness and motor skills. Overall, this research fills a critical gap in the literature regarding the impact of core strength training on young children's physical development.

Despite its strengths, the study has several limitations. The 12-week intervention may not be enough to assess long-term effects, and a longer follow-up is needed. Conducted in a single school, the findings may not be generalizable. The study also did not account for confounding factors like nutrition, sleep, or other activities, and may overlook psychological benefits. Future research should use a longitudinal approach, a larger, more diverse sample, and explore psychological and external factors affecting children's fitness.

CONCLUSION

The findings of this study indicate that children aged 6 to 8 who participated in a 12-week core strength training program experienced significant improvements in physical fitness and FMS. The experimental group demonstrated enhanced speed, explosive power, endurance, and motor coordination, outperforming the control group in tests such as sprinting, jumping, planking, back muscle strength, and jump rope. Core strength was positively associated with coordination, jumping ability, and sprint speed. However, no significant improvement was observed in the backward balance walking test, suggesting that additional or targeted training may be necessary to enhance dynamic balance. Overall, these results highlight the effectiveness of core strength training in improving FMS and physical fitness in young children.

AUTHOR CONTRIBUTIONS

Xueliang Zou conceived and designed the study, drafted the manuscript, conducted data collection, and performed the data analysis. Kurusart Konharn contributed to the study design, critically reviewed the manuscript, finalized its content, and prepared the manuscript for submission. Wichai Eungpinichpong participated in revising the manuscript. All authors have read and approved the final version of this manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICS APPROVAL

The study was approved by the Ethics Committee of Khon Kaen University (HE672147).

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Effects of combined resistance and aerobic training on body composition and functional capacity in middle-aged adults: A 12-week intervention study

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ABSTRACT

This 12-week intervention study investigated the effects of a combined resistance and aerobic training (CT) program on body composition and functional capacity in sedentary middle-aged adults ($n = 64$; 32 males, 32 females; mean age 51.3 ± 6.2 years). Participants underwent supervised CT sessions three times weekly. Outcomes were assessed at baseline, week 6, and week 12, including fat mass (FM), fat-free mass (FFM), phase angle (PhA), handgrip strength (HGS), and estimated $\text{VO}_{2\text{max}}$. Significant reductions in FM (-3.6 ± 1.1 kg) and increases in FFM ($+1.8 \pm 0.7$ kg) and PhA ($+0.6 \pm 0.2^\circ$) were observed. Functional capacity improved markedly, with HGS increasing by 4.2 ± 1.3 kg (males) and 3.1 ± 1.1 kg (females), and $\text{VO}_{2\text{max}}$ by 4.6 ± 1.5 ml/kg/min. Correlational and regression analyses revealed PhA as a strong predictor of functional gains. No significant changes in diet or physical activity outside the intervention were noted. The findings support the utility of CT in enhancing health-related outcomes during middle age and suggest that PhA may serve as a practical biomarker of exercise responsiveness.

Keywords: Sport medicine, Bioelectrical impedance analysis, Phase angle, Handgrip strength, Estimated $\text{VO}_{2\text{max}}$, Functional capacity, Resistance training, Aerobic training.

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INTRODUCTION

Middle age represents a critical life stage often characterized by insidious yet consequential alterations in physiological function and body composition. Progressive declines in skeletal muscle mass (sarcopenia) frequently occur concurrently with increases in adipose tissue, particularly visceral fat (Santanasto et al., 2017; Janssen et al., 2000). These shifts are not merely aesthetic concerns; they are intrinsically linked to diminished physical function, an elevated risk profile for metabolic diseases such as type 2 diabetes and cardiovascular disease, and an overall reduction in health-related quality of life (Cruz-Jentoft et al., 2019). While historically viewed as near-inevitable consequences of chronological ageing, a robust body of evidence now firmly establishes that these deleterious trajectories can be significantly mitigated, or even partially reversed, through targeted lifestyle interventions, with structured exercise playing a paramount role (Fragala et al., 2019).

Exercise interventions traditionally focus on either aerobic training (AT) or resistance training (RT). AT is well-recognized for its potent effects on improving cardiorespiratory fitness (CRF) and positively influencing cardiometabolic risk factors, including facilitating fat mass reduction (An, Su, & Meng, 2024) and increasing insulin sensitivity through several molecular mechanisms such as improved glucose transporter activity and reduced oxidative stress (Yaribeygi, 2019). Conversely, RT is unequivocally the most effective strategy for stimulating muscle protein synthesis, leading to increases in muscle mass, strength, and functional capacity, thereby directly counteracting sarcopenic processes (An, Su, & Meng, 2024; Marcos-Pardo, Vaquero-Cristóbal, & Huber, 2023). Given these distinct yet complementary benefits, combined or concurrent training (CT), integrating both AT and RT within the same program, emerges as a highly rational and potentially synergistic approach for comprehensively addressing the multifaceted physiological challenges of middle age (Schroeder et al., 2019). Recent meta-analytic evidence confirms that CT is as effective as AT alone for improving body composition markers, like fat mass and as effective as RT alone for enhancing lean body mass and muscle mass in middle-aged and older populations (Khalafi et al., 2025). Furthermore, concerns regarding an "*interference effect*," where concurrent modalities might blunt adaptations to one another, appear less significant for muscle hypertrophy and maximal strength development than previously thought, particularly with appropriate program design (Schumann et al., 2022), bolstering the feasibility and efficacy of CT.

Accurate assessment of intervention-induced changes necessitates appropriate measurement tools. Bioelectrical impedance analysis (BIA) offers a practical, non-invasive method for tracking changes in body composition. Beyond traditional estimates of fat mass (FM) and fat-free mass (FFM), BIA yields the phase angle (PhA), derived from the relationship between resistance and reactance. PhA is increasingly recognized not merely as an indicator of body cell mass but as a sensitive biomarker reflecting cellular membrane integrity, hydration status, and overall cellular health (Norman et al., 2012; Fernández-Jiménez et al., 2022, Rosa et al., 2025). Higher PhA values are consistently associated with better nutritional status, greater muscle quality, and favourable health outcomes (Lukaski et al., 2017; Costa Pereira et al., 2024). Moreover, recent studies suggest PhA is responsive to physical activity levels and exercise training (Yamada et al., 2022; Souza et al., 2017), potentially offering insights into the qualitative adaptations within muscle tissue beyond simple mass accretion.

Functional capacity, encompassing both muscular strength and aerobic fitness, remains a cornerstone of healthy ageing. Handgrip strength (HGS), easily measured via dynamometry, serves as a reliable surrogate for overall muscle strength and possesses significant prognostic value, predicting morbidity, mortality, and future health status (Leong et al., 2015). Similarly, aerobic capacity, often quantified as maximal oxygen

consumption ($\text{VO}_{2\text{max}}$), is a powerful independent predictor of cardiovascular health and all-cause mortality (Kodama et al., 2009). Improvements in both HGS and $\text{VO}_{2\text{max}}$ are critical targets for interventions aiming to enhance functional independence and longevity through middle age and beyond.

Despite the established importance of maintaining healthy body composition and functional capacity, and the growing interest in CT, research specifically investigating the effects of a structured, supervised, and periodized 12-week CT program in previously sedentary middle-aged adults remains somewhat limited. Furthermore, while PhA shows promise, its responsiveness to CT and its relationship with concurrent changes in established functional measures (HGS and $\text{VO}_{2\text{max}}$) within this specific demographic and intervention timeframe warrants further elucidation. Therefore, this study aimed to investigate the effects of a 12-week combined resistance and aerobic training programme on body composition (assessed via BIA, including PhA), muscle strength (measured by HGS), and aerobic capacity (estimated via submaximal testing) in sedentary adults aged 35-64 years. A secondary aim was to explore the relationships between changes in BIA-derived PhA and changes in functional parameters, evaluating its potential utility as a practical biomarker for monitoring exercise-induced adaptations in this population.

METHODS

Study design and participants

This prospective interventional study employed a single-group, pre-post design. Participants were recruited from the local community through advertisements and referrals from primary care practices. The study was carried out in accordance with the ethical requirements established by the Catholic University's research governance policies and adhered to the principles of the Declaration of Helsinki. All participants were informed about the nature, purpose, and procedures of the study and voluntarily provided written informed consent before participation. They were also informed of their right to withdraw from the study at any time without consequences. Personal data were collected and processed in compliance with the General Data Protection Regulation.

Inclusion criteria comprised: (1) age 35-64 years; (2) sedentary lifestyle (defined as <150 minutes of moderate-intensity physical activity per week); (3) body mass index (BMI) between 20-35 kg/m^2 ; and (4) medical clearance for exercise participation. Exclusion criteria included: (1) presence of cardiovascular, pulmonary, or metabolic diseases; (2) musculoskeletal conditions that would preclude exercise participation; (3) use of medications known to significantly affect body composition; and (4) participation in a structured exercise programme within the previous six months.

Of the 78 individuals initially enrolled, 64 (32 males, 32 females) completed the 12-week intervention and all assessment timepoints, representing an 82% completion rate. Reasons for dropout included time constraints ($n = 8$), illness unrelated to the intervention ($n = 3$), and relocation ($n = 3$).

Exercise intervention

Participants engaged in a 12-week supervised exercise programme consisting of three sessions per week (Monday, Wednesday, Friday), each lasting approximately 60 minutes. All sessions were conducted in a fitness facility equipped with resistance training machines and aerobic exercise equipment. Each session was supervised by qualified exercise kinesiologists with a participant-to-instructor ratio not exceeding 8:1.

The training protocol was based on recommendations to improve muscular and aerobic fitness in a healthy adult population (American College of Sports Medicine, 2009; Garber et al., 2011; Liguori, Feito, Fountaine, & Roy, 2021).

Each training session comprised:

1. Warm-up (5-10 minutes): Light aerobic activity and dynamic stretching.
2. Resistance training (25-30 minutes): Exercises targeting major muscle groups included leg press, chest press, seated row, shoulder press, and lat pull down. Training followed a periodised protocol with progression from 2 sets of 12-15 repetitions in weeks 1-4, to 3 sets of 10-12 repetitions in weeks 5-8, and 3 sets of 8-10 repetitions in weeks 9-12. Intensity was controlled using the Repetitions in Reserve (RIR) method, with participants training at an RIR of 0-2 (i.e., 0-2 repetitions left before muscular failure). Weights were adjusted individually to ensure training to near-muscular failure while maintaining proper form. A progression criterion was adopted whereby the load was increased (2–5% for upper limb, 5–10% for lower limb) when a participant successfully completed 15 (weeks 1-4), 12 (weeks 5-8) or 10 (weeks 9-12) repetitions with an RIR ≤ 1 in two consecutive sessions (Souza et al., 2017). Rest intervals ranged from 60–90 seconds between sets and 2–3 minutes between exercises.
3. Aerobic training (20-25 minutes): Performed on treadmill, stationary bicycle, or elliptical trainer. Intensity progressed from 60-65% of heart rate reserve (HRR) in weeks 1-4, to 65-70% HRR in weeks 5-8, and 70-75% HRR in weeks 9-12.
4. Cool-down (5 minutes): Light aerobic activity and static stretching.

Participants were instructed to maintain their habitual dietary patterns throughout the intervention period but completed 3-day food diaries at baseline, week 6, and week 12 to monitor for significant changes in caloric intake or macronutrient distribution.

Outcome measurements

Assessments were conducted at baseline (week 0), mid-intervention (week 6), and post-intervention (week 12). All measurements were taken by the same experienced assessors to minimise inter-rater variability.

Anthropometry and body composition

Height was measured to the nearest 0.1 cm using a wall-mounted stadiometer (Seca, Hamburg, Germany). Body mass was measured to the nearest 0.1 kg using a calibrated digital scale (Seca, Hamburg, Germany) with participants wearing light clothing and no footwear. BMI was calculated as body mass divided by height squared (kg/m^2).

Bioelectrical impedance analysis was performed using a phase-sensitive bioimpedance analyser at 50 kHz (BIA 101, BIVA Pro, Akern, Florence, Italy) following the manufacturer's guidelines and standardized protocols (Lukaski et al., 2017). Measurements were conducted in the morning following an overnight fast, with participants in a supine position on a non-conductive surface, with a leg opening of 45° compared to the median line of the body and the upper limbs abducted 30° from the trunk (National Institutes of Health [NIH], 1994). After cleansing the skin with alcohol, four disposable electrodes (Biatrodes Akern Srl, Florence, Italy) were positioned in a tetrapolar configuration: two on the dorsal surface of the right hand (at the distal metacarpals and between the distal prominences of the radius and ulna) and two on the dorsal surface of the right foot (at the distal metatarsals and between the medial and lateral malleoli) (NIH, 1994).

Prior to each test session, the accuracy of the analyser was verified and calibrated using a reference circuit according to the manufacturer's instructions.

Handgrip strength

Handgrip strength was measured using a Jamar Plus+ digital hand dynamometer (JAMAR PLUS +, Sammons Preston, Rolyon, Bolingbrook, IL, USA) following the American Society of Hand Therapists protocol (American Society of Hand Therapists, 2015). Participants were seated with their elbow flexed at 90°, forearm in neutral position, and wrist in slight extension (0–30°). After a familiarization phase, participants performed three maximal voluntary contractions (MVCs) of the dominant hand, each lasting at least 3 seconds. A rest interval of 60 seconds was provided between attempts. The peak force output was recorded and expressed in kilograms (kg). The average measurement, as well as the highest value, was chosen for analysis (Lupton et al., 2022).

Aerobic capacity

Aerobic capacity was estimated using the Åstrand-Ryhming submaximal bicycle ergometer test (Åstrand & Ryhming, 1954; Gerber et al., 2025), administered on a calibrated cycle ergometer (Monark 828E, Monark Exercise AB, Vansbro, Sweden). Heart rate was continuously monitored throughout the test using a chest strap sensor (Polar H10) in conjunction with a Polar Vantage V2 multisport watch (Polar Electro Oy, Kempele, Finland), ensuring a high temporal resolution and validated reliability in submaximal testing contexts.

To minimize the risk of premature fatigue and to ensure participant safety, initial workloads were intentionally conservative: 60 Watts for men and 40 Watts for women. Following a 2–3 minute warm-up phase, workload was incrementally adjusted so that perceived exertion approached a level of 13 on the Borg Rating of Perceived Exertion scale (RPE), while heart rate progressively increased toward a predetermined target zone.

The target heart rate range was stratified by age group: 130–160 beats per minute (bpm) for participants aged ≤40 years, and 120–150 bpm for those above 40 years. Participants were instructed to maintain a cadence of 60–70 revolutions per minute (rpm) over a standard six-minute test duration. If heart rate stabilized—defined as a variation of no more than ±5 bpm over the final two minutes—the test was concluded. In cases where stabilization was not achieved, the protocol was extended by an additional one or two minutes, up to a maximum of eight minutes total.

Heart rate was recorded at the end of each minute, alongside subjective measures of effort (Borg RPE scale) and affective valence. Post-test, maximal oxygen uptake ($\text{VO}_{2\text{max}}$) was estimated following the procedure described by Buono et al. (1989), using the mean heart rate of the final two minutes and the corresponding workload. This value was subsequently corrected for the age factor.

Physical activity and dietary monitoring

Physical activity outside the intervention was monitored using the International Physical Activity Questionnaire (IPAQ) (Mannocci et al., 2010) at baseline, week 6, and week 12. Participants also completed 3-day food diaries (two weekdays and one weekend day) at the same timepoints. Nutritional intake was analysed using dietary analysis software (Nutritics, Dublin, Ireland).

Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics for Windows, version 27.0 (IBM Corp., Armonk, NY, USA). Data were initially assessed for normality using the Shapiro–Wilk test. Descriptive

statistics are reported as mean $\pm$ standard deviation (SD) for normally distributed variables and as median with interquartile range (IQR) for non-normally distributed data.

Changes in outcome measures over the three timepoints (baseline, week 6, and week 12) were analysed using repeated-measures analysis of variance (RM-ANOVA) for normally distributed data. The assumption of sphericity was tested using Mauchly's test; when this assumption was violated, the Greenhouse–Geisser correction was applied to adjust the degrees of freedom. Post-hoc comparisons were performed using the Bonferroni adjustment for multiple testing.

For non-normally distributed variables, Friedman's test was employed, followed by Wilcoxon signed-rank tests for pairwise comparisons. A Bonferroni correction was also applied to the Wilcoxon tests to control for type I error inflation due to multiple comparisons.

Sex differences at baseline and in change scores were analysed using independent samples t-tests or Mann–Whitney U tests, depending on the data distribution and homogeneity of variances (verified with Levene's test).

Associations between changes in body composition (e.g., fat mass, fat-free mass, phase angle) and functional outcomes (handgrip strength and estimated $\text{VO}_{2\text{max}}$) were assessed using Pearson's product-moment or Spearman's rank correlation coefficients, depending on the normality and linearity of the data.

Multiple linear regression analyses were conducted to identify independent predictors of changes in handgrip strength and estimated $\text{VO}_{2\text{max}}$. Predictor variables included changes in fat-free mass, fat mass, and phase angle. Prior to model inclusion, multicollinearity was assessed via variance inflation factor (VIF), and residuals were examined for normality, linearity, and homoscedasticity. The Durbin–Watson statistic was used to assess independence of residuals. Statistical significance was set at $p < .05$ (two-tailed). Effect sizes were calculated as partial eta-squared (η^2) for ANOVA (with thresholds of small ≥ 0.01 , medium ≥ 0.06 , and large ≥ 0.14) and Cohen's d for t-tests (small ≥ 0.2 , medium ≥ 0.5 , large ≥ 0.8), providing a complementary perspective on the practical significance of findings.

RESULTS

All outcome variables met the assumptions for normal distribution as verified by the Shapiro–Wilk test; therefore, parametric analyses were applied throughout.

Participant characteristics

The baseline characteristics of the 64 participants who completed the study are presented in Table 1. The sample included equal numbers of males and females with a mean age of 51.3 ± 6.2 years. No significant differences were observed between males and females in age or BMI, though males had significantly higher baseline values for fat-free mass, phase angle, handgrip strength, and estimated $\text{VO}_{2\text{max}}$ (all $p < .001$).

Adherence and adverse events

The mean attendance rate for exercise sessions was $89.3 \pm 6.7\%$ (32.1 ± 2.4 out of 36 sessions). No significant sex differences in attendance were observed (males: $88.7 \pm 7.1\%$, females: $89.9 \pm 6.3\%$, $p = .472$). No serious adverse events related to the intervention were reported. Minor adverse events included delayed-onset muscle soreness ($n = 15$), which resolved within the first two weeks, and non-specific knee discomfort ($n = 3$), which was addressed through exercise modification.

Table 1. Baseline characteristics of study participants.

Characteristic	All (n = 64)	Males (n = 32)	Females (n = 32)	p-value
Age (years)	51.3 ± 6.2	50.8 ± 6.5	51.8 ± 5.9	.528
Height (cm)	171.4 ± 9.1	178.2 ± 6.4	164.6 ± 5.3	<.001
Body mass (kg)	78.6 ± 12.3	84.5 ± 10.4	72.7 ± 11.2	<.001
BMI (kg/m ²)	26.7 ± 3.2	26.6 ± 2.9	26.8 ± 3.5	.806
Fat mass (kg)	25.9 ± 7.4	21.8 ± 5.7	30.0 ± 6.4	<.001
Fat-free mass (kg)	52.7 ± 10.5	62.7 ± 5.4	42.7 ± 4.3	<.001
Phase angle (°)	5.6 ± 0.7	6.0 ± 0.6	5.2 ± 0.5	<.001
Handgrip strength (kg)	32.8 ± 10.1	41.3 ± 6.3	24.3 ± 4.5	<.001
Estimated VO _{2max} (ml/kg/min)	27.4 ± 5.8	30.6 ± 5.1	24.2 ± 4.7	<.001

Note. Data presented as mean ± standard deviation. p-values refer to independent t-tests comparing males and females.

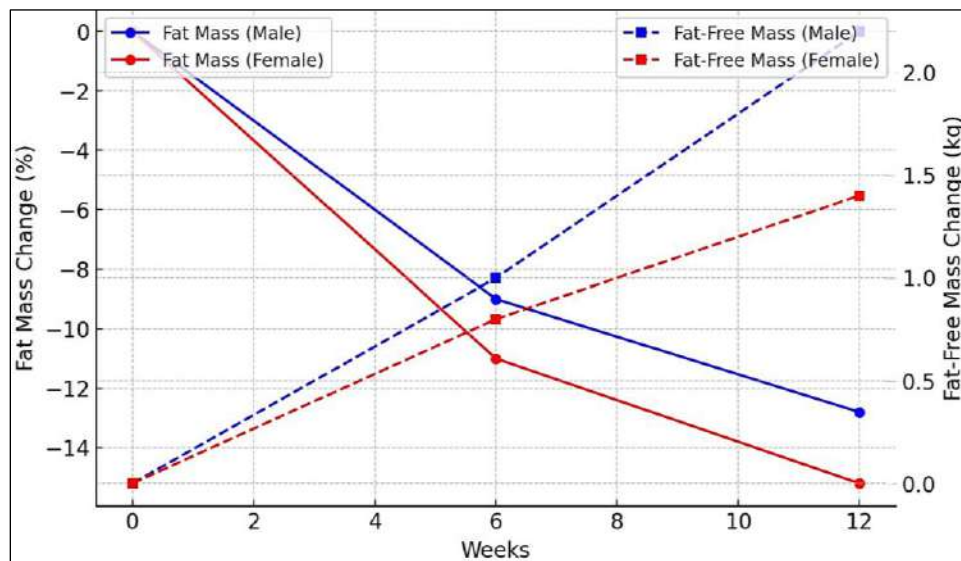
Changes in body composition

Table 2 presents the changes in body composition parameters across the intervention period. Significant improvements were observed in all measured parameters from baseline to week 12 (all $p < .001$). Notably, while significant reductions in body mass and fat mass were observed by week 6, significant increases in fat-free mass and phase angle were only detected at week 12.

Table 2. Changes in body composition parameters throughout the 12-week intervention.

Parameter	Baseline	Week 6	Week 12	Effect size (η^2)
Body mass (kg)	78.6 ± 12.3	77.1 ± 11.9*	76.3 ± 11.6*†	0.78
BMI (kg/m ²)	26.7 ± 3.2	26.2 ± 3.1*	25.9 ± 3.0*†	0.76
Fat mass (kg)	25.9 ± 7.4	23.9 ± 7.1*	22.3 ± 6.8*†	0.84
Fat-free mass (kg)	52.7 ± 10.5	53.2 ± 10.4	54.5 ± 10.7*†	0.67
Phase angle (°)	5.6 ± 0.7	5.8 ± 0.7	6.2 ± 0.8*†	0.72

Note. Data presented as mean ± standard deviation. p-values refer to repeated-measures ANOVA. *Significantly different from baseline ($p < .05$). †Significantly different from week 6 ($p < .05$).



Note. It shows: A sharper decline in fat mass (%) during the first six weeks, more pronounced in females. A more substantial increase in fat-free mass (kg) in the latter half of the intervention, with males gaining more in absolute terms.

Figure 1. Changes in body composition over the intervention period.

Sex-specific analyses revealed that males exhibited greater absolute increases in fat-free mass than females (2.2 ± 0.8 kg vs. 1.4 ± 0.6 kg, $p < .001$), whereas females demonstrated greater relative reductions in fat mass ($-15.2 \pm 4.3\%$ vs. $-12.8 \pm 3.9\%$, $p = .022$). However, improvements in phase angle were similar between sexes (males: $+0.6 \pm 0.2^\circ$, females: $+0.6 \pm 0.3^\circ$, $p = .842$).

Figure 1 illustrates the changes in body composition parameters throughout the intervention period. The most pronounced changes in fat mass occurred during the first six weeks, while fat-free mass increases were more substantial during the latter half of the intervention.

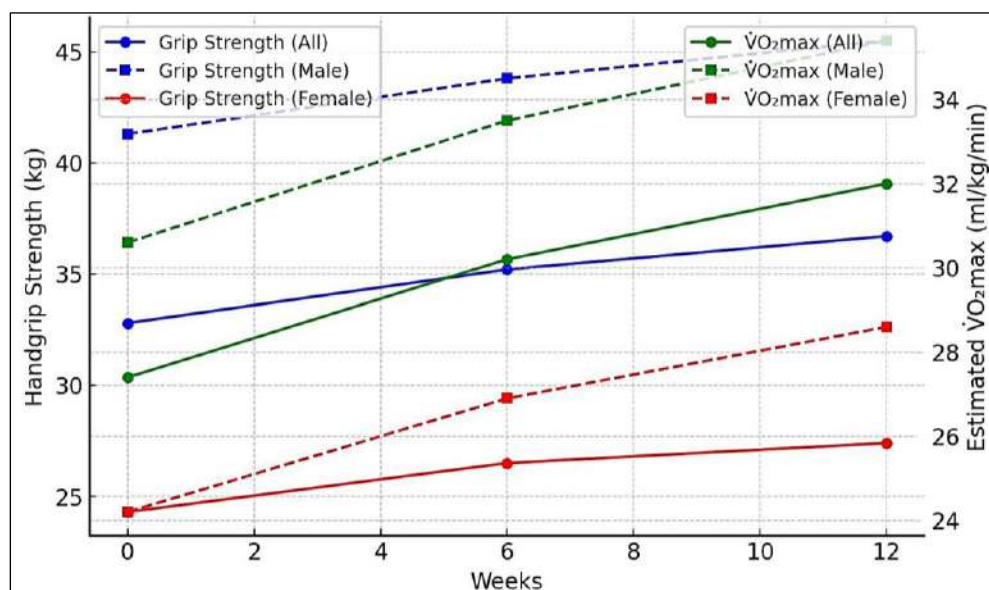
Changes in functional parameters

Significant improvements in handgrip strength and estimated $\text{VO}_{2\text{max}}$ were observed over the 12-week intervention (Table 3). Unlike body composition parameters, significant improvements in functional measures were evident by week 6 and continued through week 12.

Table 3. Changes in functional parameters throughout the 12-week intervention.

Parameter	Baseline	Week 6	Week 12	Effect size (η^2)
<i>Handgrip strength (kg)</i>				
All	32.8 ± 10.1	$35.2 \pm 10.3^*$	$36.7 \pm 10.5^{*\dagger}$	0.74
Males	41.3 ± 6.3	$43.8 \pm 6.5^*$	$45.5 \pm 6.7^{*\dagger}$	0.71
Females	24.3 ± 4.5	$26.5 \pm 4.7^*$	$27.4 \pm 4.8^{*\dagger}$	0.68
<i>Estimated $\text{VO}_{2\text{max}}$ (ml/kg/min)</i>				
All	27.4 ± 5.8	$30.2 \pm 6.0^*$	$32.0 \pm 6.3^{*\dagger}$	0.81
Males	30.6 ± 5.1	$33.5 \pm 5.3^*$	$35.4 \pm 5.5^{*\dagger}$	0.79
Females	24.2 ± 4.7	$26.9 \pm 4.9^*$	$28.6 \pm 5.1^{*\dagger}$	0.75

Note. Data presented as mean $\pm$ standard deviation. p -values refer to repeated-measures ANOVA. *Significantly different from baseline ($p < .05$). $\dagger$ Significantly different from week 6 ($p < .05$).



Note. The trends indicate: A steady increase in handgrip strength for all groups, with males showing higher absolute values. A similar steady increase in $\text{VO}_{2\text{max}}$, with males having higher absolute values but relative improvements being comparable between sexes.

Figure 2. The progressive improvements in handgrip strength (kg) and estimated $\text{VO}_{2\text{max}}$ (ml/kg/min) over the 12-week intervention.

Males demonstrated greater absolute improvements in handgrip strength compared to females (4.2 ± 1.3 kg vs. 3.1 ± 1.1 kg, $p < .001$), but relative improvements were similar ($10.2 \pm 3.2\%$ vs. $12.8 \pm 4.5\%$, $p = .078$). Similarly, while absolute increases in estimated $\text{VO}_{2\text{max}}$ were greater in males (4.8 ± 1.6 ml/kg/min vs. 4.4 ± 1.4 ml/kg/min, $p = .275$), relative improvements were comparable ($15.7 \pm 5.2\%$ vs. $18.2 \pm 5.9\%$, $p = .076$).

Figure 2 illustrates the progressive improvements in handgrip strength and estimated $\text{VO}_{2\text{max}}$ throughout the intervention period. The rate of improvement was relatively constant across the 12 weeks for both parameters.

Relationships between changes in body composition and functional parameters

Correlation analyses revealed significant associations between changes in body composition parameters and functional outcomes (Table 4). Notably, increases in phase angle demonstrated the strongest correlations with improvements in both handgrip strength and estimated $\text{VO}_{2\text{max}}$.

Table 4. Correlations between changes in body composition and functional parameters over the 12-week intervention.

Parameter	Change in handgrip strength	Change in estimated $\text{VO}_{2\text{max}}$
Change in body mass	-0.31*	-0.38**
Change in fat mass	-0.42**	-0.49**
Change in fat-free mass	0.56**	0.48**
Change in phase angle	0.68**	0.57**

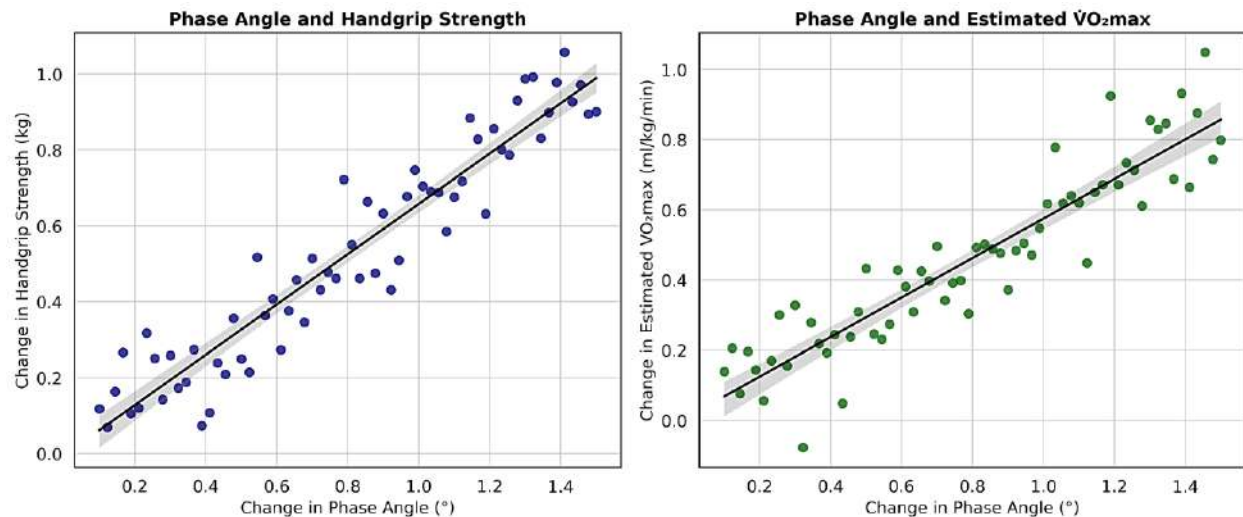
Note. Values represent Pearson correlation coefficients (r). * $p < .05$, ** $p < .001$.

Multiple regression analysis (Table 5) identified changes in phase angle ($\beta = 0.45$, $p < .001$) and fat-free mass ($\beta = 0.32$, $p = .003$) as independent predictors of improvements in handgrip strength ($R^2 = .53$, $p < .001$). Similarly, changes in phase angle ($\beta = 0.38$, $p < .001$), fat mass ($\beta = -0.29$, $p = .007$), and fat-free mass ($\beta = 0.26$, $p = .012$) were identified as independent predictors of improvements in estimated $\text{VO}_{2\text{max}}$ ($R^2 = .48$, $p < .001$).

Table 5. Multiple linear regression analyses predicting changes in functional parameters.

Dependent variable: Δ Handgrip strength				
Predictor	β	SE	95% CI	p-value
Δ Phase angle	0.45	0.07	0.31 – 0.59	<.001
Δ Fat-free mass	0.32	0.09	0.13 – 0.51	.003
$R^2 = .53$, $p < .001$; VIF < 2.0				
Dependent variable: $\Delta \text{VO}_{2\text{max}}$				
Predictor	β	SE	95% CI	p-value
Δ Phase angle	0.38	0.08	0.23 – 0.53	<.001
Δ Fat-free mass	0.26	0.10	0.06 – 0.45	.012
Δ Fat mass	-0.29	0.10	-0.48 – -0.10	.007
$R^2 = .48$, VIF < 2.0				

Figure 3 illustrates the relationship between changes in phase angle and improvements in functional parameters. The scatter plots demonstrate positive linear relationships, with greater increases in phase angle associated with more substantial improvements in both handgrip strength and estimated $\text{VO}_{2\text{max}}$.



Note. Left plot: A positive linear correlation between phase angle changes and handgrip strength improvements ($r = 0.68$). Right plot: A positive linear correlation between phase angle changes and estimated VO_{2max} improvements ($r = 0.57$).

Figure 3. Relationships between changes in phase angle and improvements in functional parameters.

Physical Activity and dietary monitoring

Analysis of IPAQ data revealed no significant changes in physical activity outside the intervention (baseline: 95.3 ± 42.6 MET-min/week, week 12: 103.5 ± 46.2 MET-min/week, $p = .326$). Similarly, analysis of food diaries indicated no significant changes in total energy intake (baseline: 2187 ± 462 kcal/day, week 12: 2135 ± 445 kcal/day, $p = .247$) or macronutrient distribution (all $p > .05$) throughout the intervention period.

DISCUSSION

This study demonstrates that a 12-week combined resistance and aerobic training programme significantly improves body composition, muscle strength, and aerobic capacity in sedentary middle-aged adults. Our findings gain considerable support from recent meta-analyses confirming the efficacy of such concurrent approaches. Furthermore, our results highlight the potential utility of BIA-derived phase angle (PhA) as a practical biomarker for monitoring exercise-induced adaptations, a notion bolstered by emerging research linking PhA to muscle quality.

Body composition changes

The observed reductions in body mass (-2.3 kg on average) and particularly fat mass (-3.6 kg) align with the established benefits of exercise for improving body composition in middle-aged adults. A comprehensive 2025 meta-analysis by Khalafi and colleagues involving over 2800 middle-aged and older adults confirms that concurrent training (CT) is as effective as aerobic training (AT) alone for reducing various measures of adiposity, including fat mass and body fat percentage. Importantly, their analysis suggests CT may even yield superior reductions in body fat percentage compared to AT alone in middle-aged individuals and those with obesity, particularly over longer durations (>24 weeks) (Khalafi et al., 2025). While our 12-week intervention achieved comparable fat mass reductions (-3.6 kg) to the 8-month combined training study by Willis et al. (2012) (-3.7 kg), potentially attributable to our structured, supervised, and progressive design, the findings from Khalafi et al. (2025) provide robust, contemporary backing for the effectiveness of the combined modality itself.

The increases in fat-free mass (FFM, +1.8 kg) are particularly noteworthy given the relatively short intervention duration and the typical age-related decline in muscle mass (Cruz-Jentoft et al., 2019). This magnitude of gain is consistent with the ~1.1 kg increase reported by Peterson et al. (2011) following resistance training (RT) in adults over 50, and again, finds strong support in recent meta-analytic data. Khalafi et al. (2025) confirmed that CT is as effective as RT alone for increasing lean body mass (LBM) and muscle mass. Furthermore, a direct comparison meta-analysis by An et al. (2024) found that while AT surpasses RT for improving cardiorespiratory fitness and reducing body mass, RT is superior for enhancing LBM. This underscores the strategic advantage of our combined approach, effectively leveraging the distinct benefits of both modalities to achieve simultaneous improvements in fat loss and muscle gain within a single program. Notably, the temporal patterns observed – predominant fat mass reductions in the first six weeks, with more substantial FFM increases in the latter half – may reflect an initial emphasis on lipolytic processes followed by the more delayed onset of significant muscle hypertrophy (Boutcher, 2011; Schoenfeld, 2010), a common pattern in response to initiating structured exercise

Functional improvements

The significant improvements in handgrip strength (HGS; males: +4.2 kg; females: +3.1 kg) demonstrate the effective transferability of whole-body resistance training to this clinically relevant measure of overall muscle function. These gains likely reflect both neuromuscular adaptations, such as enhanced neural drive and motor unit recruitment, and the underlying muscle hypertrophy suggested by the FFM increase (Schoenfeld, 2010). The importance of combined training for strength parameters is further supported by recent large-scale observational data. Sung et al. (2022), using nationwide Korean data, found that participation in combined aerobic and resistance exercise was most consistently associated with preserved HGS in middle-aged adults compared to single-modality or no exercise.

Similarly, the substantial improvements in estimated $\text{VO}_{2\text{max}}$ (+4.6 ml/kg/min, a ~17% increase) underscore the potent cardiorespiratory benefits of the combined training protocol. This aligns well with the meta-analysis by An et al. (2024), which confirmed the superiority of AT over RT for improving $\text{VO}_{2\text{max}}$, highlighting the crucial contribution of the aerobic component of our intervention. Our observed $\text{VO}_{2\text{max}}$ increase is comparable to the 15.9% gain reported by Huang et al. (2016) following 12 weeks of aerobic interval training in a similar population. The use of the Astrand-Rhyming submaximal test, while an estimation, has demonstrated reasonable validity in comparable populations (Hartung et al., 1995; Gerber et al., 2025), lending confidence to these findings.

Phase angle as a biomarker

Perhaps the most novel finding of this study is the strong positive correlation between increases in BIA-derived phase angle and improvements in both HGS ($r = 0.68$) and estimated $\text{VO}_{2\text{max}}$ ($r = 0.57$). Phase angle, reflecting cellular membrane integrity and function, is increasingly recognized as a marker of cellular health and nutritional status (Norman et al., 2012; Rosa et al., 2025). The results strongly suggest it may also serve as a sensitive, non-invasive indicator of positive functional adaptations to exercise training. The mean PhA increase (0.6°) observed is consistent with, and indeed slightly larger than, the 0.34° increase reported by Souza et al. (2017) after 12 weeks of resistance training in older women.

Crucially, recent research provides a potential mechanistic link for our findings. A 2024 systematic review and meta-analysis by Costa Pereira and colleagues specifically investigated PhA as a marker of muscle quality. They found moderate positive correlations between PhA and skeletal muscle radiodensity (indicating less fat infiltration) and inverse correlations with muscle echogenicity, alongside weaker correlations with strength per unit mass (MQI) (Costa Pereira et al., 2024). This emerging evidence suggests that the exercise-

induced increase in PhA we observed may reflect not only greater muscle mass (FFM) but also improvements in the quality and composition of the muscle tissue itself, which likely underpins the enhanced functional capacity (HGS and $\text{VO}_{2\text{max}}$). Our finding that PhA increased similarly between sexes despite significantly different absolute FFM gains further supports the idea that PhA captures qualitative adaptations beyond simple mass accretion. The independent predictive value of PhA changes for functional improvements in our regression analyses strengthens its potential utility. Given BIA's accessibility and non-invasiveness, PhA could represent a practical biomarker for monitoring the efficacy of exercise interventions in diverse settings.

Sex differences

The analyses revealed expected baseline differences and subsequent sex-specific responses in absolute terms. Males exhibited greater absolute increases in FFM and HGS, consistent with higher baseline values and greater muscle mass (Janssen et al., 2000). However, the relative improvements in HGS (~10% vs ~13%), estimated $\text{VO}_{2\text{max}}$ (~16% vs ~18%), and the absolute increase in phase angle were remarkably similar between males and females, suggesting comparable underlying adaptive responsiveness to the combined training stimulus.

This aligns with a growing body of evidence. While absolute adaptations often differ, relative changes are frequently similar when programmes are appropriately designed (Roberts et al., 2020). Specifically, regarding muscle growth, a very recent Bayesian meta-analysis by Refalo et al. (2025) confirmed that while absolute muscle size increases slightly favour males post-RT, relative increases are similar between sexes. However, some nuance regarding concurrent training specifically is emerging. A 2024 meta-analysis by Huiberts et al. found a small interference effect (blunted gains) for lower-body strength in males undertaking CT, but not in females, while upper-body strength and $\text{VO}_{2\text{max}}$ adaptations showed no sex difference. While we measured HGS (upper body), these findings warrant consideration in future studies examining whole-body responses. The greater relative reduction in fat mass observed in females in this study (-15.2% vs -12.8%) may reflect known sex differences in adipose tissue metabolism, such as greater lipolytic sensitivity during exercise in females (Lundsgaard & Kiens, 2014). Overall, our findings support the notion that both middle-aged men and women benefit substantially and comparably in relative terms from combined training.

Clinical and practical implications

The improvements observed carry significant clinical and practical weight. The average increases in HGS (3.1-4.2 kg) exceed the minimal clinically important difference of 2.5 kg proposed by Bohannon (2019), suggesting meaningful functional gains. Likewise, the average $\text{VO}_{2\text{max}}$ improvement (+4.6 ml/kg/min) surpasses the 3.5 ml/kg/min threshold associated with reduced mortality risk (Blair et al., 1995).

From a practical standpoint, these findings strongly endorse current physical activity guidelines advocating combined resistance and aerobic training for middle-aged adults (World Health Organization, 2020). The effectiveness of this approach is further cemented by recent meta-analyses (An et al., 2024; Khalafi et al., 2025) and supported by population-level data linking combined exercise to better strength outcomes (Sung et al., 2022). Our progressive overload, structured, and supervised intervention serves as a potential template for effective exercise prescription in this population. Furthermore, the identification of PhA as a responsive biomarker, potentially reflecting improvements in muscle quality (Costa Pereira et al., 2024), offers a practical, non-invasive tool for healthcare practitioners to monitor intervention efficacy and provide feedback, complementing traditional functional assessments.

Limitations and future directions

Several limitations warrant consideration. The single-group pre-post design precludes definitive causal conclusions, although the stability of external physical activity and diet mitigates confounding factors. The use of BIA, while validated (Malavolti et al., 2003) and practical, lacks the precision of DXA for body composition. Similarly, estimating $\text{VO}_{2\text{max}}$ via a submaximal protocol, though validated (Hartung et al., 1995) and appropriate for this initially sedentary cohort, is less precise than direct measurement.

Future research should employ randomised controlled designs comparing combined training against single modalities or different CT configurations (intensities, volumes, sequencing). Longitudinal studies are needed to assess the durability of these adaptations and the long-term predictive value of PhA changes. Further investigation into the cellular and molecular mechanisms underpinning the relationship between PhA improvements and functional gains, potentially exploring the sex-specific nuances highlighted by Huijberts et al. (2024), would significantly enhance our understanding of exercise-induced adaptations.

CONCLUSIONS

A 12-week combined resistance and aerobic training programme significantly improves body composition, muscle strength, and aerobic capacity in sedentary middle-aged adults. The strong correlations between increases in BIA-derived phase angle and improvements in functional parameters suggest its potential utility as a biomarker for monitoring exercise-induced adaptations. These findings support current physical activity guidelines advocating combined training approaches for middle-aged adults and highlight the importance of structured, progressive exercise programming for optimising health outcomes in this population.

AUTHOR CONTRIBUTIONS

Ferdinando Cereda: conceptualization, methodology, formal analysis, data curation, investigation, writing – original draft, visualization, supervision, project administration. Luigi Marano: formal analysis, data curation, investigation, writing – review & editing.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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Bone mineral density in female runners, swimmers, and water polo athletes: Comparisons across sports with different impacts

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ABSTRACT

Bone mineral density (BMD) is a measure of bone health which reflects risk for osteoporosis. Different types of exercise induce divergent impact on the skeleton influencing accrual of BMD. Previous research reported that female collegiate athletes in aquatic sports had lower BMD than other athletes and controls. **PURPOSE:** The goal of this study was to conduct a modern comparison of BMD of athletes in weight-bearing and non-weight-bearing sports with normally active controls. **METHODS:** Height, weight, and calcium intake was assessed in collegiate females (20.0 ± 1.3 years); 39 runners, 9 swimmers, 16 water polo players, and 24 controls. BMD and bone free lean mass were measured via dual-energy x-ray absorptiometry (DXA) at baseline and 5 months later. **RESULTS:** When controlling for calcium intake and lean mass, there were no statistical differences between groups in BMD at the anterior-posterior (AP) spine, lateral spine, trochanter, total hip, and whole body. At the femoral neck (FN), water polo players had greater BMD than swimmers (0.922 ± 0.030 vs. 0.790 ± 0.033 g/cm², $p = .005$). Longitudinally, increases in BMD between visits occurred for swimmers at the AP spine ($p = .028$), lateral spine ($p = .049$), FN ($p = .049$), and trochanter ($p = .018$) and for controls at whole body ($p = .008$). **CONCLUSION:** Bone health in female aquatic athletes was similar to controls and runners, except at the FN where BMD of swimmers was less than water polo players. Some females may continue to accrue BMD in college years. Modern training methods among female college athletes may lead to similar bone health even in sports with different skeletal impact.

Keywords: Sport medicine, Osteoporosis, Calcium, College, Weight-bearing, Aquatic sports.

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INTRODUCTION

Osteoporosis is a chronic disease featuring low bone mineral density (BMD) and skeletal fragility. When BMD is lower than normal, individuals are at a higher risk for osteoporosis and suffer increased risk for fracture due to reduced bone strength. Osteoporosis may occur if peak bone mass is not achieved during youth which emphasizes the value of optimizing bone health as an emerging adult (Gunter et al., 2011). Research shows that lifestyle behaviours account for 20-40% of adult bone mass, with special emphasis on calcium intake and physical activity during youth for optimal development of peak bone mass (Weaver et al., 2016). Approximately 10 million Americans have been diagnosed with osteoporosis and another 43 million suffer from low bone mass which predisposes someone to osteoporosis (Wright et al., 2014). According to the U.S. Centers for Disease Control, women are nearly 5 times more likely than men to have osteoporosis at the femoral neck or lumbar spine after the age of 50 (Sarafrazi et al., 2021). One way for women to lower risk for poor skeletal health is to participate in sports, especially during adolescence and young adult years.

Weight-bearing activity and participation in sports with impact loading achieve an osteogenic effect that enhances bone properties, including bone size, architecture, strength (Kohrt et al., 2004). In vivo analysis of BMD may be one of the best measures of bone strength accounting for up to 60% of the strength of the skeleton (Weinstein, 2000). Children should engage in impact activities for 10-20 minutes, three times a week in order to stimulate proper bone formation prior to peak bone mass accrual (Kohrt et al., 2004). As adults, maintaining healthy BMD levels can be achieved by engaging in weight-bearing physical activity with high bone-loading forces, 3-5 times a week and resistance training 2-3 times per week, for 30-60 minutes (Kohrt et al., 2004). Following these exercise prescriptions may help decrease risk for osteoporosis and fracture later in life while stimulating the necessary osteogenic response to achieve optimal peak bone mass and maintain healthy BMD levels throughout life.

Participation in collegiate athletics has expanded greatly in the last 50 years for female athletes. National championships for female collegiate athletes in the United States began in 1967, with gymnastics added in 1969, swimming in 1970, cross country running in 1982, and women's water polo in 2001 (Bell, 2007; Whitaker, 2023). The number of women competing in the National Collegiate Athletic Association (NCAA) increases annually, with a record-breaking 235,735 female athletes in 2024 (McGuire, 2025). To improve performance and help avoid injury, strength and resistance training has increased greatly among female athletes. Resistance exercise has become an essential component of high-level training protocols because of the substantial performance benefits. In addition, resistance training is widely known to benefit skeletal health and increase BMD (Haff and Triplett, 2015; Kohrt et al., 2004).

Studies conducted in the late 1990's by Taaffe et al. reported that females in non-weight-bearing sports, such as swimming, exhibit lower BMD than those in weight-bearing sports, like gymnastics and running (Taaffe et al., 1997; Taaffe et al., 1995). For female athletes, the beneficial weight-bearing stimulus of gymnastics during adolescence facilitated peak bone mass development that outweighed the stimulus of the forceful muscle contractions of swimming (Taaffe et al., 1995). Of note, was Taaffe's report that a control group of non-athletes in those studies had greater BMD than swimmers at the femoral neck and trochanter, even though the swimmers engaged in about 22 hours of training each week. Taaffe et al. attributed this finding to the amount of time swimmers spent in a non-weight-bearing environment which would negate the positive effect of swimming exercise (Taaffe et al., 1995). Longitudinally Taaffe et al. found that gymnasts experience the greatest long-term benefits to BMD which should be attributed to the high-impact bone loading characteristics of the sport. Over 12 months, the changes in BMD experienced by gymnasts were greater than both

swimmers and controls (Taaffe et al., 1997), however this research did not make direct comparison between swimmers and runners.

In an investigation measuring bone strength via peripheral quantitative computed tomography, water polo athletes had similar skeletal measures to controls in the lower leg but were greater than controls at the distal radius (Greene et al., 2012). Other researchers found evidence that BMD redistribution occurs among male water polo athletes from the lower extremities to the upper extremities (Kavouras et al., 2006). When compared to handball athletes and controls, water polo athletes had greater BMD in the upper extremities but less BMD in the lower extremities than controls. Direct comparisons of bone health between female swimmers, water polo players, runners, and controls are lacking but necessary to better understand the influence of the varying load patterns of these sports.

The purpose of this study was to revisit previous findings by comparing the BMD of athletes in weight-bearing and non-weight-bearing sports with normally active controls. Specifically, we sought to assess bone health in current female collegiate runners, swimmers, and water polo players. We also aimed to assess whether female collegiate athletes experienced changes in BMD over one competitive season (about 5 months). We hypothesized that BMD in female athletes of weight-bearing and non-weight-bearing sports would be more similar today than in results from the 1990's (Taaffe et al., 1997; Taaffe et al., 1995) due to a greater emphasis on resistance training and better understanding of peak bone mass development during adolescence.

MATERIALS AND METHODS

Participants

The female athletes in the study were recruited from NCAA Division 1 cross country, swimming, and water polo teams. Normally active females of a similar age were recruited from the same institution to serve as controls. Participants were excluded if they were pregnant or under the age of 18. The runners trained 9-10 bouts in a week accumulating about 100 km. Swimmers exercised 8-11 times per week for 1-3 hours each session. Water polo athletes practiced 8-9 sessions per week averaging 2-4 hours per day. To evaluate changes in bone health over time, participants were asked to return to repeat testing at the conclusion of their competitive season, approximately 5 months later.

Prior to joining the study, all volunteers were educated about study procedures and gave informed consent to participate. The study methods and procedures were approved by a university Institutional Review Board for the Protection of Human Subjects. This research was carried out in accordance with the ethical standards of the National Health Council and to the Declaration of Helsinki for research involving human subjects. Each researcher was educated on ethical standards of the Helsinki Declaration prior to contributing to the study.

Anthropometrics and questionnaires

Height in centimetres and weight in kilograms were measured two times each on an electric scale with attached stadiometer (Seca Accu-Hite, Columbia, MD, USA). Participants were asked to wear lightweight clothing and remove shoes or any bulky clothing. The average of the two measures is reported.

Demographics and menstrual information were collected via a health history questionnaire. Calcium intake was assessed via rapid assessment method (Henry and Almstedt, 2009). Participants were asked to identify the calcium-containing foods and supplements on the food frequency questionnaire consumed in the last week and how many servings of each. The questionnaire was scored by summing all dietary calcium intake for the week and dividing by seven.

Physical activity was quantified using a Physical Activity Questionnaire (Pereira et al., 1997). Participants recorded which activities they participated in regularly for the last three months and how many minutes a week they spent doing them. The Physical Activity Questionnaire (PAQ) was scored by summing the number of MET-hours per week. The PAQ also provided information about cross-training activities, including resistance training.

Bone mineral density and lean mass

BMD analysis of the anterior-posterior (AP) spine, lateral spine, trochanter, femoral neck (FN), and whole body was made using dual-energy x-ray absorptiometry (DXA; Hologic Delphi A, Waltham, MA, USA). Our laboratory produces a 1.0% test-retest reliability using DXA for scans of the spine, hip, and whole body. DXA scans were taken by the same technician at each visit. Lack of pregnancy was confirmed via urine dipstick test to ensure safety prior to beginning scans. The whole body scan was used to calculate bone free lean mass (BFLM) in kilograms which was used as a covariate for statistical analysis.

Statistical analysis

Data was analysed using IBM SPSS version 27 (IBM Corporation, Armonk, New York) statistical package for Windows. An alpha level of .05 or less was used to establish statistical significance. Differences in age, height, weight, body mass index (BMI), BFLM, calcium intake, and physical activity were compared using an analysis of variance, with a Bonferroni post-hoc test. To evaluate differences in BMD at baseline, a two-tailed analysis of covariance (ANCOVA) was performed with a Bonferroni correction. Because lean mass accounts for more than 20% of variance in BMD (Ho-Pham et al., 2014), BFLM was used as a covariate. Statistical analyses were also controlled for calcium intake. Changes in BMD over time were evaluated with a repeated-measures ANCOVA, also with Bonferroni correction. Effect size was evaluated using Cohen's *d* when significant differences were discovered. Effect sizes were interpreted as large (≥ 0.8), medium (0.5-0.79), small (0.2-0.49), or non-existent (0-0.19) (Cohen, 1988).

RESULTS

In total, 88 females volunteered for the study, including 39 runners, 9 swimmers, 16 water polo players, and 24 controls. Participant demographics are displayed in Table 1. Age between groups did not differ. Height, weight, BMI, and BFLM were significantly different between groups. Specifically, BFLM was greater in swimmers and water polo athletes than in runners or controls. Calcium intake of runners was significantly greater than all other groups. Physical activity per week also differed among groups. Water polo athletes recorded the most MET-hours per week, and as expected, all athletes recorded more MET-hours than the controls. Beyond running, the cross country athletes did two, 1-hour resistance training sessions and two, 1-hour aqua jogging sessions weekly. Water polo athletes were resistance training 3 times per week in the off-season months (September-December) and 2 times per week while in season (January-May). Swimmers and runners were resistance training 2 times per week during the academic year. Among all volunteers, 43% ($n = 38$) were using hormonal contraceptives. Three runners, one swimmer, and one water polo player were experiencing amenorrhea when they enrolled in the study.

Table 2 displays the average bone health variables at baseline. When controlling for calcium intake and BFLM, all groups were found to have similar BMD at the AP spine, lateral spine, trochanter, total hip, and whole body. However, swimmers had 14.3% lower BMD than water polo players at the FN ($p = .004$, $d = 1.96$).

At visit two 18 runners, 11 water polo players, 8 swimmers, and 24 controls returned for follow-up DXA scans. Reasons for not returning for the longitudinal analysis included a busy schedule, lack of interest, leaving the

team, injuries which prevented training, and illness with COVID-19. Figure 1 displays changes in BMD among the four groups at each bone site. The longitudinal analysis showed that returning swimmers increased in BMD during the five-month period between tests. Significant increases were measured for swimmers at the AP spine ($p = .028$, $d = 1.05$), lateral spine ($p = .049$, $d = 1.67$), FN ($p = .049$, $d = 0.50$), and trochanter ($p = .018$, $d = 0.58$). BMD changed by 1.8% at the AP spine, 3.7% at the lateral spine, 4.2% at the FN, and 2.1% at the trochanter. Controls, runners, and water polo athletes experienced small, non-significant changes in BMD during the 5-month period. Swimmers were the only athletes to experience substantial gains in bone mass, while controls had a significant increase in whole body BMD ($p = .008$, $d = 0.43$).

Table 1. Demographic data for participants at baseline. Data is reported as mean $\pm$ standard deviation for quantitative variables or as percent and number for nominal variables.

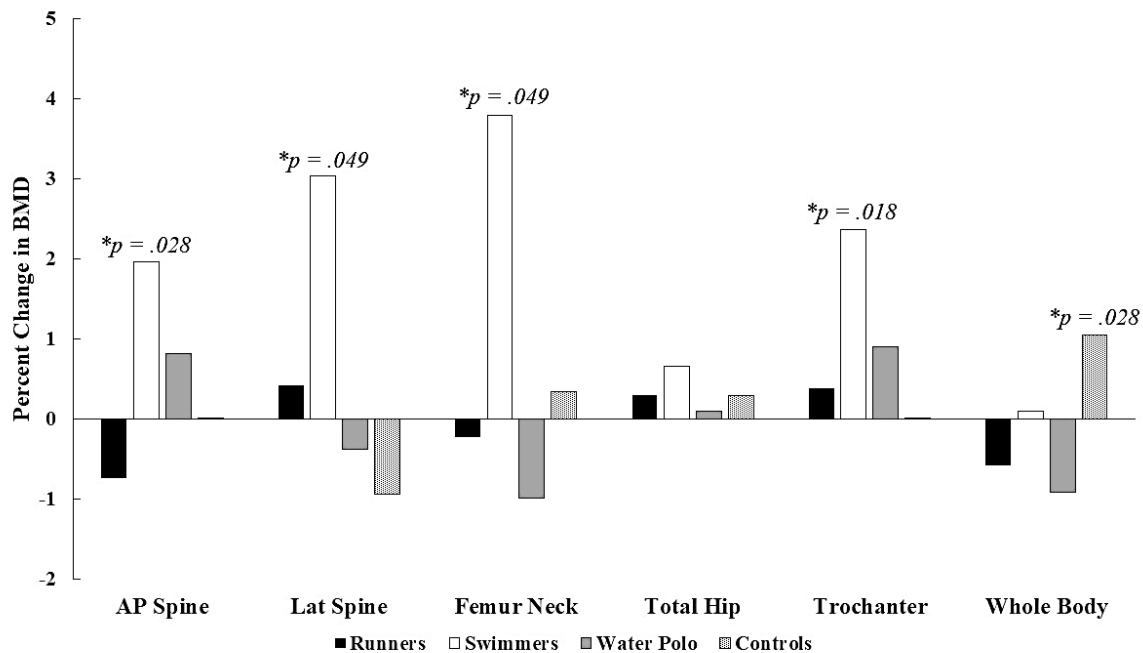
Variables	Runners n = 39	Swimmers n = 9	Water polo n = 16	Controls n = 24	p-value
Age (years)	19.95 $\pm$ 1.50	19.47 $\pm$ 1.07	20.52 $\pm$ 1.58	19.75 $\pm$ 0.58	NS
Height (cm)	164.13 $\pm$ 5.74	166.78 $\pm$ 1.07	169.20 $\pm$ 8.24	162.24 $\pm$ 6.02	WP>C $p = .004$
Weight (kg)	54.28 $\pm$ 5.20	66.38 $\pm$ 4.77	75.84 $\pm$ 12.76	54.79 $\pm$ 5.05	WP>S $p = .012$ S>C $p < .001$ R<S, WP $p < .001$
BMI (kg/m ²)	20.13 $\pm$ 1.42	23.89 $\pm$ 2.04	26.48 $\pm$ 4.20	20.88 $\pm$ 1.20	WP>S $p = .036$ S>C $p = .004$ R<S, WP $p < .001$
Bone free lean mass (kg)	39.66 $\pm$ 3.63	45.00 $\pm$ 3.56	49.26 $\pm$ 6.31	37.40 $\pm$ 3.18	S>R $p = .004$ S>C $p < .001$ WP>C, R $p < .001$
Race and Ethnicity	61.5% W (n = 24) 33.3% H (n = 13) 5.1% A (n = 2)	77.8% W (n = 7) 22.2% A (n = 2)	81.3% W (n = 13) 18.8% H (n = 3)	37.5% W (n = 9) 12.5% H (n = 3) 45.8% A (n = 11) 4.2% Other (n = 1)	
Calcium intake (mg/day)	1365.02 $\pm$ 643.89	409.33 $\pm$ 126.22	632.31 $\pm$ 325.15	884.31 $\pm$ 357.74	R>C $p = .002$ R>S, WP $p < .001$
Physical activity (MET-hrs/wk.)	110.13 $\pm$ 7.34	108.82 $\pm$ 11.73	188.26 $\pm$ 9.09	23.40 $\pm$ 7.19	C<R, S, WP $p < .001$ WP>R, S $p < .001$
Menstrual status	E: 35.9% (n = 4) O: 10.3% (n = 4) A: 7.7% (n = 3) HC: 46.2% (n = 18)	E: 44.4% (n = 4) O: 0 A: 11.1% (n = 1) HC: 44.4% (n = 4)	E: 62.5% (n = 10) O: 0 A: 6.3% (n = 1) HC: 31.3% (n = 5)	E: 50% (n = 12) O: 4.2% (n = 1) A: 0 HC: 45.8% (n = 11)	

Note. NS = nonsignificant, WP = water polo, S = swimmers, R = runners, C = controls, BMI = body mass index, W = white, H = Hispanic, A = Asian, MET-hrs/wk. = metabolic equivalent hours per week, E = eumenorrheic, O = oligomenorrheic, A = amenorrheic, HC = using hormonal contraceptives.

Table 2. Mean bone mineral density (BMD) and standard error at each site.

BMD (g/cm ²)	Runners n = 39	Swimmers n = 9	Water Polo n = 16	Controls n = 24
AP Spine	0.971 $\pm$ 0.019	0.937 $\pm$ 0.038	1.039 $\pm$ 0.035	1.010 $\pm$ 0.024
Lateral Spine	0.762 $\pm$ 0.019	0.699 $\pm$ 0.039	0.755 $\pm$ 0.034	0.763 $\pm$ 0.023
Femoral Neck	0.886 $\pm$ 0.017	0.790 $\pm$ 0.033*	0.922 $\pm$ 0.030	0.890 $\pm$ 0.020
Trochanter	0.789 $\pm$ 0.015	0.702 $\pm$ 0.031	0.758 $\pm$ 0.028	0.774 $\pm$ 0.019
Total Hip	1.018 $\pm$ 0.017	0.912 $\pm$ 0.035	0.979 $\pm$ 0.032	1.004 $\pm$ 0.021
Whole Body	1.092 $\pm$ 0.013	1.020 $\pm$ 0.026	1.055 $\pm$ 0.024	1.050 $\pm$ 0.016

Note. * $p = .004$, S significantly lower BMD at the femoral neck than water polo athletes when controlling for bone-free lean mass and calcium. BMD = bone mineral density, AP = anterior-posterior.



Note. *Significant change between initial and follow up visit when controlling for BFLM and calcium. BMD = bone mineral density, AP = anterior-posterior, Lat = lateral

Figure 1. Percent change in BMD between baseline and 5-months later at six bone sites. Controls showed no change at the AP spine or trochanter.

DISCUSSION

We report that when controlling for calcium intake and BFLM, female collegiate athletes in weight-bearing (running) and non-weight-bearing sports (swimming and water polo) have similar BMD to each other and controls, except at the FN. Swimmers in this study showed significantly lower BMD than water polo players at this important bone site. Further, despite having lower BMD at the FN in cross-sectional comparisons, swimmers were the only athletes in this study that showed significant increases in BMD over the 5-month competitive season with meaningful changes in both views of the spine and two of the hip sites (FN and trochanter). Even though, changes in BMD of 1.8-4.2% may appear small compared to some physiological measures, previous research shows this is clinically relevant and may relate to a reduction in fracture risk of 13-42%, later in life (Wasnich and Miller, 2000). Non-athletes also increased significantly in BMD of the whole body. Perhaps, the principle of initial values partially explains why the swimmers increased in BMD and runners or water polo athletes did not (Winters-Stone and Snow, 2003). The initial values principle of exercise science suggests that people with the lowest baseline values have the largest propensity towards improvements due to training.

Lower BMD observed at the FN in swimmers is particularly important due to the clinical significance of bone mass at this site. The FN is the primary bone site used for diagnosis of osteoporosis and assessment of fracture risk (Leslie et al., 2011). Large epidemiological studies establish the FN as the bone site most predictive of future fractures (Johnell et al., 2005). Thus, the lower BMD at the FN in the female collegiate swimmers of this study is especially concerning. On the other hand, the roughly 2.0-3.8% increase in BMD at four bone sites among swimmers suggests that these women are still working towards peak bone mass.

Despite the substantial hours of non-weight-bearing activity in the pool each week, the female swimmers in this study increased bone mass over 5 months of training. These results differ from research of more than 20 years ago showing that collegiate swimmers had lower BMD than runners, gymnasts, and even non-athletes (Taaffe et al., 1995). Further, the swimmers in the study by Taaffe et al. exhibited <1% change in BMD after 12 months of training (Taaffe et al., 1997).

Perhaps the modern incorporation of prescribed resistance training programs aimed to improve performance can help explain the differences in results reported in this investigation compared to prior work. While vague in nature, for swimmers, Taaffe et al. reported “*approximately 2 h/week each of resistance training and aerobic activity (running, cycling)*” in their 1995 study and 3-5 hours per week of “*resistance training and aerobic activity*” for the athletes in their 1997 study. Swimmers and water polo athletes in the current study were resistance training 2-3 days per week for approximately one hour, performing multi-joint, core exercises such as squats, deadlifts, pull-ups, bent-over rows, and bench press.

We report similar bone health at the spine and whole body for runners, swimmers, water polo athletes, and controls. This contrasts with previous research that the weight-bearing nature of running may protect BMD at the hip and whole body, but not the spine (Barrack et al., 2008; Tam et al., 2018). Female distance runners were found to have significantly greater BMD than controls, displaying an advantage in bone mass, especially of the whole body (McCormack et al., 2019). However, some research shows that running may be beneficial to bone health in college-age males but not females (Infantino et al., 2021). Runners frequently exhibit lower than expected bone mass and increased risk for fractures when practicing dietary restraint or when energy availability is lacking (Barrack et al., 2008; Fredericson et al., 2007; McCormack et al., 2019; Tenforde et al., 2018; Tenforde et al., 2015). The current investigation could be strengthened by including analysis of energy availability.

Runners in this study were consuming significantly more calcium than the other groups and achieving more the recommended dietary allowance (RDA) of 1000 mg per day (IOM, 2011). On average, swimmers were consuming 41% of the RDA, water polo athletes 63%, and controls 88%. Calcium intake was used as a covariate in this analysis, since it was significantly different between groups and correlated to BMD at the whole body ($r = 0.303$, $p = .004$). Adequate consumption of calcium is vital to achieving optimal peak bone mass in addition to meeting the physical demands of sport (Sale and Elliott-Sale, 2019; Weaver et al., 2016). While the benefit of calcium on bone health is well established, some research indicates that high impact exercise is more important than dietary calcium for building bone strength (Welch et al., 2008). Thus, comprehensive analysis of bone health includes assessment of dietary intake and weight-bearing physical activity. Aquatic athletes in this study may benefit from increasing dietary calcium intake.

A strength of this study is the examination of water polo athletes which widens the population of non-weight-bearing athletes, providing more depth to the data compared to previous studies which only assessed swimmers. As a newer collegiate sport in the USA, there is less research involving water polo players and this study contributes to building up the literature. The non-weight-bearing environment in aquatic sports is similar but stresses the body in different ways which could contribute to the differences in bone health observed here between swimmers and water polo players. This study also emphasizes evaluation of multiple (six) bone sites for a comprehensive evaluation of bone health throughout the skeleton. In future investigations, it would be beneficial to increase the sample size of the study to provide a more generalizable view of bone health in different sports. Longitudinally our study did not have a high number of participants which makes it difficult to extrapolate the findings. Further, analysis of musculoskeletal injuries and serum levels of vitamin D would also provide a better understanding of holistic bone health.

CONCLUSIONS

In summary, we report that bone health in female aquatic athletes was similar to controls and runners, except at the FN where BMD of swimmers was less than water polo players. These findings are somewhat contradictory to work from the 1990s that reported lower BMD in aquatic athletes, even in comparison to non-athletes. Perhaps modern approaches to training for female collegiate athletes leads to similar bone health even in sports with different skeletal impact. Of the three groups of athletes, swimmers were the only ones to display significant increases in bone health over 5 months of training.

AUTHOR CONTRIBUTIONS

All authors were involved with study conceptualization, data curation, analysis, funding acquisition, investigation, and methodology. EK and HA wrote the original draft, reviewed, and edited this paper. All authors read and approved the final version of the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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Study of menstrual cycle in training load variability in female basketball players

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ABSTRACT

The menstrual cycle is a key factor influencing athletic performance. This study analysed its impact on the training load of female basketball players over a two-month period using a case series design with ten participants. Descriptive analysis, variation coefficients, mixed linear models, and regression techniques were applied to assess the relationship between menstrual phases and training variables. The results indicate that a significant portion of performance variability is linked to specific menstrual phases, with notable individual differences. Understanding these fluctuations is essential for optimizing training programs that align with athletes' physiological states. During phases of hormonal stability, such as the follicular phase, high-intensity training can be prioritized to maximize physical output, focusing on explosive movements, accelerations, and decelerations. Conversely, during the luteal or menstrual phase, when hormonal fluctuations may reduce fatigue tolerance, training should emphasize moderate-intensity or technical sessions to support recovery while maintaining performance. Incorporating menstrual cycle-aware training adaptations can improve athletic performance, reduce injury risk, and enhance overall well-being, underscoring the need for a more individualized approach to female athlete conditioning.

Keywords: Sport medicine, Women, Workload, Athletic performance.

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INTRODUCTION

Recently, the menstrual cycle has become an object of special interest in sport sciences' studies, attempting to examine possible variations in the performance of athletes based on the phase of the cycle they are in. Hormonal variability, particularly in oestrogen and progesterone, can impact the response to exercise in women (Davis & Hackney, 2016). This raises the question of whether there are specific moments or phases in the menstrual cycle where performance differs. If so, taking the menstrual cycle into account during training could make a significant difference. Before delving deeper, it is necessary to gain a better understanding of the menstrual cycle, its phases, and the variability of the most crucial hormones. In fact, the participation of women in sports has experienced a remarkable increase, rising from 2% at the Paris Olympic Games in 1900 to 49% at the Tokyo 2020 Olympic Games (Committee, 2021). These has led to numerous research efforts in the field (McNulty et al., 2020).

Theoretically, a menstrual cycle lasts 28 days, but the normal range is between 21 and 35 days and can even extend up to 40 days (Serret et al., 2012). The menstrual cycle is divided into four phases based on the major hormonal changes that occur (Giménez-Blasi et al., 2022): Menstrual, follicular, ovulatory, and luteal (see Table 1).

Table 1. Phases of the menstrual cycle and key hormonal changes.

Phase	Hormonal changes
Menstrual (days 1 – 6)	Oestrogen and progesterone are low.
Follicular (days 7 – 12)	Oestrogen begins to rise, reaching its peak before ovulation.
Ovulatory (day 13 – 16)	As a result of the peak oestrogen at the end of the follicular phase, there is an increase in LH hormone that triggers the release of the egg from its follicle (ovulation).
Luteal (days 17 – 28)	Progesterone reaches its peak, and oestrogen has a noticeable increase midway through this phase.

Note: The duration range of each phase has been established using an ideal 28-day cycle as a representative reference.

The potential influence of the hormones on variations in athletic performance is based on the hypothesis of the anabolic and neuroexcitatory effects of oestrogen, contributing to the increase in strength and power levels, particularly during the follicular phase (Davis & Hackney, 2016). In contrast, during the luteal phase, higher levels of progesterone may inhibit cortical excitability and partially limit these benefits, potentially reducing performance capacity (Oosthuyse & Bosch, 2010).

The specific effects of hormonal phases on athletic performance provide a solid foundation for tailoring training plans to the menstrual cycle. During the follicular phase, increased levels of oestrogen are associated with enhanced strength production, power output, and recovery capacity, making it an optimal period for incorporating high-intensity exercises such as strength training, plyometrics, and explosive actions. Conversely, in the luteal phase, elevated progesterone levels can limit these capabilities by reducing neuromuscular efficiency and increasing perceived fatigue. As a result, training during this phase may benefit from a focus on moderate-intensity activities, technical skill development, and active recovery, ensuring performance is maintained without overburdening the athlete.

In women's basketball, the performance optimization process involves respect for fundamental principles of sports training, such as individualization and specificity (Bompa & Buzzichelli, 2018; Soto et al., 2023). Quantifying training load is an essential resource to obtain objective, valid, and useful information for the coaching staff regarding the performance of the players (Ibáñez & Feu, 2023). Those training programs have predominantly been designed considering the male sex, without addressing the physiological differences that

may exist between men and women. It is evident that this has a negative impact on the preparation of female athletes, as training programs lack adaptability (Taylor et al., 2017). The wide hormonal variability that a woman may experience in her different cycles, coupled with significant differences between women, highlights the difficulty of establishing general training guidelines that are applicable to all players (Reed & Carr, 2000). Therefore, it is necessary to understand hormonal fluctuations and their implications on performance by analysing the performance of each athlete on an individualized basis, allowing to determine if the athlete experiences moments and phases where her performance is lower and adapt the training according to her individual response (McNulty et al., 2020).

Regarding strength training, Kissow et al. (2022) highlighted that training during the first half of the menstrual cycle appears to be superior in terms of improving strength and muscle mass. In this regard, Davis and Hackney (2016) conclude that poorer outcomes are expected at the end of the luteal phase and during the menstrual phase due to hormonal variations, especially in progesterone and oestrogen levels.

In relation to muscular endurance, anaerobic power, and hormonal changes, Arazi et al. (2019) did not find a performance loss in any of the evaluated capacities during different phases of the menstrual cycle. Additionally, the study by Romero-Moraleda et al. (2019) investigated fluctuations in muscular performance in the half-squat exercise and found no significant differences in the analysed variables between different phases of the cycle. However, Pallavi et al. (2017) examined variations in muscular strength and fatigue during menstrual cycle phases in young adult women. They concluded that cyclic hormonal variation increases muscular strength in the follicular phase. On the other hand, Julian et al. (2017) study focused on analysing the effects of different menstrual cycle phases on sub-elite female soccer players. A considerable decrease in Yo-Yo Test performance was observed during the latter half of the luteal phase compared to the menstrual phase, although similar effects were not found in jumps and sprints.

Based on the previous literature, most current studies on physical performance in women's basketball have overlooked the menstrual cycle of players or have considered it in laboratory conditions with isolated tests. These conditions differ significantly from a real training situation, especially in team sports like basketball, where factors and processes such as decision-making and environmental perception can impact the players' final performance (Grant et al., 2020). Consequently, it is advisable to investigate what happens in a real context, as evidenced, and carried out in recent research (Arenas-Pareja et al., 2023). The objective of this work was to analyse the impact of the menstrual cycle on the training load of basketball players in the actual training context, aiming to understand this relationship and identify the individual characteristics of each player.

MATERIALS AND METHODS

Design

This research was considered *ex post facto* following the classification of Montero and León (2007), due to the fact that the analysis of the data was carried out after its collection. This type of research is common in sport sciences due to the ecological context of data collection, being carried out in the natural context of sport without manipulation of variables or experimental design. The aim is to collect data as close as possible to what happens in reality, without interfering in the training or in the performance of the players. Therefore, none of the players' behaviours that could interfere with the results of the measurement are conditioned or modified. The players are expressly asked to maintain their daily habits and routines for the duration of the study as well as for the rest of the season. This ensures that, once the results are obtained, the conclusions

and practical applications resulting from the research can be directly applied in training without modifying other issues.

Population and sample

This research was conducted with a team from that compete at national level. Twelve basketball players participated (age: 20.92 ± 4.72 years; height: 171.33 ± 8.60 cm) in this study. In the context of sports training, it is important to note that the number of players analysed is generally small due to the competitive nature of the environment. However, this inherent limitation in competitive sports does not compromise the validity of the results obtained (Lago-Peñas et al., 2019). Finally, only 10 players who met the inclusion criteria were included in the study.

Inclusion criteria

To be considered a case study, the player should: (i) belong to the analysed team; (ii) have participated in at least 70% of the training sessions; (iii) not take contraceptive pills, at least, in the last six months; (iv) have regular menstrual cycles; (v) not have suffered injuries in the last four weeks of training.

The information presented in this study comes from 8 training sessions: data were collected once a week for eight weeks (two months), this ensured that the structure of the session was very similar to reduce the contamination of the tasks design on the load generated. The tasks designs were developed by the team's coaching staff based on the sporting objectives, maintaining the same structure that they had been developing since the beginning of the season, with the same specific warm-up and full game tasks (5vs5). The duration of the sessions was 67.52 ± 14.80 minutes. The variability in the duration of the session is due to the distance to the match or the instructions of the coach.

Variables

The independent variable was the menstrual cycle, categorized into four levels based on the four phases of the cycle: Menstrual, Follicular, Ovulatory, and Luteal. Sixteen dependent variables were recorded (see Table 2), divided into two groups: internal load and external load. All of them considered the training session as a covariate.

Table 2. Summary of the variables analysed during the study.

	Variable	Description (measurement units)
Internal load	HRmax	Maximum heart rate (ppm).
	HRavg	Average heart rate (ppm).
	mhHR	Covered meters at $>85\%$ of maximum heart rate (m).
External load	mDEXP	Covered meters at $> 1.12 \text{ m/s}^2$ (m).
	m1218	Covered meters at 12-18 km/h (m).
	m > 18	Covered meters at $> 18 \text{ km/h}$ (m).
	ACCmax	Numbers of accelerations at $> 2 \text{ m/s}^2$ (n).
	DECmax	Numbers of decelerations at $> 2 \text{ m/s}^2$ (n).
	ACCavg	Average acceleration (m/s^2).
	DECavg	Average deceleration (m/s^2).
	mhACC	Covered distance at $> 3 \text{ m/s}^2$ (m).
	mhDEC	Covered distance at $< -3 \text{ m/s}^2$ (m).
Neuromuscular	hIMP	Impacts $> 8 \text{ G}$ (n).
	hTOFF	Take Offs $> 3 \text{ G}$ (n).
	hLAND	Landings $> 5 \text{ G}$ (n).
	PL	Player load (u. a.).

Instruments

Data recording was carried out using the WIMU Pro system (Agile Sports Technologies, Inc., Nebraska; Huld 2023). Ultra-wideband (UWB) technology was utilized for positioning, which records sports information indoors with greater measurement accuracy due to the placement of antennas (Figure 1). The UWB system is calibrated to the reference field by being distributed along the perimeter and recognizing it as the reference system (Bastida-Castillo et al., 2019).

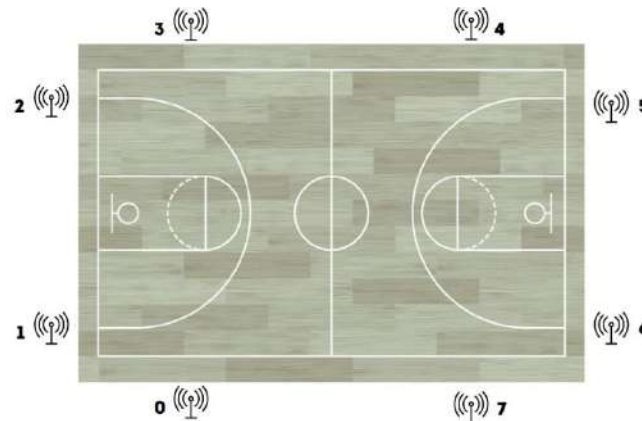


Figure 1. Distribution of the UWB antenna system on a basketball court (own elaboration).

Given that some of the mentioned methods for identifying the menstrual cycle phase tend to have higher economic costs, this research utilized a menstrual calendar mobile application. Consequently, the use of mobile applications for tracking menstrual cycles in elite athletes has become increasingly common. Various sports organizations, such as Chelsea Football Club, Brisbane Lions, and the U.S. national women's soccer and swimming teams, have adopted this methodology (Ayling, 2020; Kleyn, 2020). Athletes record their menstrual cycle and related symptoms, and coaches and the technical staff have access to this data to identify performance changes during different phases of the cycle. To maintain an accurate record of the menstrual cycle, the Clue application (Biowink GmbH, Germany) was used, which was familiarized with each player to keep individualized monitoring on their mobile device (Engelmann et al., 2018; Nogueira et al., 2018). This choice was based on its easy accessibility and feasibility, allowing for the recording of each stage of the menstrual cycle, as well as a range of physical, psychological, and activity changes from the first day of the cycle (Li et al., 2020; Palomino, 2021). In addition, the study by Liu et al. (2019) shows different studies regarding the validity of the app, as well as studying the menstrual cycle from a large amount of data extracted from the app.

The Clue app is the top-rated app on Android by users and the most downloaded, being widely used in scientific research (Liu et al., 2019). It consists of a menstruation calendar in which, through the collection of different data, a prediction of fertile days, menstrual cycles and ovulation is made; offering an analysis of past and current menstrual cycles. It is a tool that also works with adolescents and irregular menstrual cycles. For predictions it is necessary to add the dates of menstruation and intensity of flow, mood and premenstrual symptoms. It also allows you to record your physical activity, track your libido and record symptoms of premenstrual syndrome.

Procedure

All players and coaching staff were informed about the protocol to be followed. Similarly, any queries or concerns that arose were addressed, providing necessary clarifications. Informed consent was obtained from

all participants by signing a written document prior to data collection but after the protocol was reviewed by the Bioethics and Biosafety Commission of the University of Extremadura and approved on 19/12/2022 according to document 210/2022. The research was conducted following the ethical criteria of the Declaration of Helsinki (2013) and was approved by the University's Bioethics Committee (210/2022). Prior to the start of data collection, all players were interviewed to determine the status of their menstrual cycle. Details such as the current phase of the cycle, the duration of the last cycle, the use of oral contraceptives, cycle regularity, among other relevant aspects, were collected. Based on the obtained information, the selection of participating players was carried out.

Until now, most current studies on physical performance in women's basketball have overlooked the menstrual cycle of players or have considered it in laboratory conditions with isolated tests. These conditions differ significantly from a real training situation, especially in team sports like basketball, where factors and processes such as decision-making and environmental perception can impact the players' final performance (Grant et al., 2020). Consequently, it is advisable to investigate what happens in a real context, as evidenced and carried out in recent research (Arenas-Pareja et al., 2023).

To analyse each training session, the UWB system was calibrated approximately one hour before the start. In addition, the WIMU Pro inertial devices were synchronized with the UWB system using ANT+ technology. Each player received a GARMIN™ heart rate monitor and a WIMU Pro inertial device, which was placed in a specific anatomical harness adjusted on the upper back (Figure 2). This protocol was implemented before each training session, following a familiarization period during the first data collection session (García-Rubio et al., 2024).

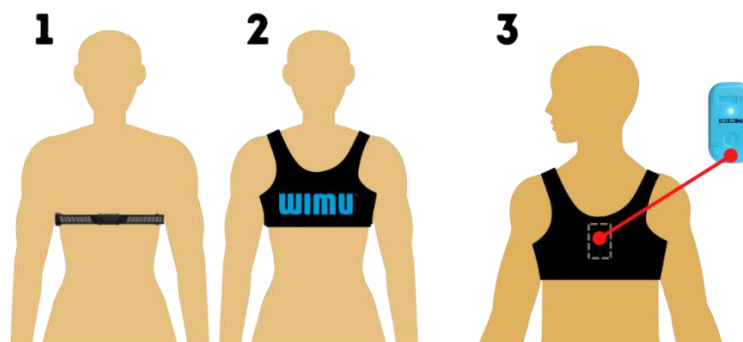


Figure 2. Placement of the heart rate monitor and the inertial device (own elaboration). 1 and 2: Front view; 3: Rear view.

Data analysis

Firstly, normality in the distribution of the dependent variables was tested using the Shapiro-Wilk test ($p > .05$). Secondly, the coefficient of variation (CV) was utilized to calculate the variability of each of the dependent variables and assess the relative dispersion of data at both the group and individual levels. In this case, the CV serves as an indicator of the homogeneity of a sample, as a smaller value indicates a more homogeneous sample. The dataset is considered homogeneous if the coefficient of variation is less than or equal to 30%; however, if the coefficient of variation is greater, the dataset is deemed heterogeneous (Field, 2013).

Next, a Mixed Linear Model (MLM) was applied to consider the fixed effects of the menstrual cycle, as well as the random effects capturing individual differences and variations among team players. Within the random

effects, the Intraclass Correlation Coefficient (ICC) was considered. The ICC is typically calculated as the ratio of between-group variance to the sum of variances between groups and within groups. It can be interpreted as the proportion of total variation explained by the grouping structure of the model. In this case, the ICC allows us to understand what amount of variation can be explained by differences among the team players. Similarly, linear regression was used as a statistical technique to estimate the magnitude and direction of the menstrual cycle effects individually for each player on the internal and external load endured. This can help us understand the relationships between the studied variables and draw conclusions about the impact of the menstrual cycle on performance at an individual level. In both analyses, the training session was consistently considered as a covariate. All statistical analyses were conducted using the software Jamovi 2.3.18 (The Jamovi Project, 2022). The significance level was set at $p < .05$.

RESULTS

Based on the data recorded in the mobile application used by each player, the following information was obtained from our sample: participants have an average cycle duration of 31.35 days, with a standard deviation of ± 5.12 days. Next, the results of the descriptive and variability analysis of the investigated variables at the group level are presented in Table 3.

Table 3. Descriptive and variability analysis of external and internal load indicators at the group level.

	Variable	X	SD	CV (%)
Internal load	HRmax	184.82	13.89	8
	HRavg	143.58	16.39	11
	mhHR	1386.73	834.01	60
External load	mDEXP	342.16	88.82	26
	m1218	453.13	164.12	36
	m > 18	34.68	31.41	91
	ACCmax	4.71	1.33	28
	DECmax	(-)4.74	(-)1.12	24
	ACCavg	0.74	0.10	14
	DECavg	(-)0.74	(-)0.09	12
	mhACC	71.39	37.19	52
	mhDEC	74.20	32.83	44
	hIMP	26.04	18.02	69
	hTOFF	5.38	4.42	82
	hLAND	8.86	9.44	107
	PL	58.70	10.87	19

Note: Distance covered at $> 1.12\text{m/s}^2$ (mDEXP); Distance covered at 12-18km/h (m1218); Distance covered at over 18km/h (m > 18); Maximum acceleration (ACCmax); Maximum deceleration (DECmax); Average acceleration (ACCavg); Average deceleration (DECavg); Distance covered at $> 3\text{m/s}^2$ (mhACC); Distance covered at $> -3\text{m/s}^2$ (mhDEC); Maximum heart rate (HRmax); Average heart rate (HRavg); Distance covered at $> 85\%$ of maximum heart rate (mhHR); Impacts $> 8\text{G}$ (hIMP); Take-offs $> 3\text{G}$ (hTOFF); Landings $> 5\text{G}$ (hLAND); Neuromuscular load (PL). Values with a Coefficient of Variation (CV) greater than 30% have been highlighted in bold.

Analysing the Coefficient of Variation (CV) of the recorded variables, it is observed that landings above 5G (hLAND) exceed 100% variation, followed by distance covered at over 18km/h (m > 18) with 91%, and take-offs above 3G (hTOFF) with a variability of 81%.

Table 4 shows the results obtained from the evaluation of relative dispersion through the coefficient of variation in the analysed variables for each player.

Table 4. Variability analysis of external and internal load indicators at the individual level.

Variables		CV									
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Internal load	HRmax	3	16	5	1	1	3	2	15	1	4
	HRavg	8	19	5	6	3	5	8	18	4	6
	mhHR	64	95	81	34	27	48	48	56	24	50
External load	mDEXP	27	39	17	24	5	22	25	19	15	22
	m1218	29	66	26	26	9	39	29	29	31	32
	m > 18	93	99	60	123	81	61	37	83	145	85
	ACCmax	31	41	22	40	16	31	15	32	13	20
	DECmax	26	31	19	39	15	24	9	25	9	13
	ACCavg	15	12	8	12	7	9	13	8	6	7
	DECavg	17	12	6	12	6	8	12	8	6	6
	mhACC	48	76	28	42	27	28	39	43	64	29
	mhDEC	57	46	24	46	24	39	34	24	45	51
	hIMP	43	96	34	57	31	48	54	45	48	58
	hTOFF	57	122	50	146	95	46	57	78	55	67
	hLAND	60	86	50	54	68	35	51	138	48	87
	PL	18	27	12	19	9	9	22	14	9	9

Note: Player (P); Distance covered at $> 1.12\text{m/s}^2$ (mDEXP); Distance covered at 12-18km/h (m1218); Distance covered at over 18km/h ($m > 18$); Maximum acceleration (ACCmax); Maximum deceleration (DECmax); Average acceleration (ACCavg); Average deceleration (DECavg); Distance covered at $> 3\text{m/s}^2$ (mhACC); Distance covered at $> -3\text{m/s}^2$ (mhDEC); Maximum heart rate (HRmax); Average heart rate (HRavg); Distance covered at $> 85\%$ of maximum heart rate (mhHR); Impacts $> 8\text{G}$ (hIMP); Take-offs $> 3\text{G}$ (hTOFF); Landings $> 5\text{G}$ (hLAND); Neuromuscular load (PL). Values with a Coefficient of Variation (CV) greater than 30% have been highlighted in bold.

The individual results reveal that players 5 and 3 exhibit the least performance variation in the recorded variables, as their Coefficient of Variation (CV) exceeds 30% in only 4 out of 16 variables and in 5 out of 16 variables, respectively. For player 5, the variable hTOFF (take-offs $> 3\text{G}$) has the highest CV at 95%. In contrast, player 3 records the highest CV in the variable mhHR (distance covered at more than 85% of her maximum heart rate) with a value of 81%. On the other hand, player 2 shows the greatest variation in performance, with a CV exceeding 30% in 11 out of the 16 collected variables, and the variable hTOFF (take-offs $> 3\text{G}$) exhibits the highest variability at 122%. Four variables stand out, with all players exceeding 30% in Coefficient of Variation (CV): Distance covered at over 18km/h ($m > 18$); Impacts $> 8\text{G}$ (hIMP); Take-offs $> 3\text{G}$ (hTOFF); Landings $> 5\text{G}$ (hLAND). In three of these four variables ($m > 18$, hTOFF, and hLAND), at least one player records a CV higher than 100%.

Regarding the mixed linear model, the results are presented in Table 5. In the model, the menstrual cycle phase explains 40%, 34%, and 41% of the total variability in performance for average acceleration (ACCavg), average deceleration (DECavg), and distance covered at $> 85\%$ of the maximum heart rate (mhHR), respectively. Simultaneously, the Intraclass Correlation Coefficient (ICC) indicates that individual differences between players account for approximately 38%, 33%, and 40% of the total variability in average acceleration (ACCavg), average deceleration (DECavg), and distance covered at $> 85\%$ of the maximum heart rate (mhHR), respectively. This suggests that both the menstrual cycle phase and individual player characteristics are important factors to consider when analysing team performance.

Further below, you can observe the results obtained from the linear regression analysis (see to Table 6), which examines the impact of the menstrual cycle on the performance variation of each player.

Table 5. Results of the mixed linear model.

	Variable	R ² conditional	p-Value	ICC
Internal load	HRmax	.01	.98	0.00
	HRavg	.32	.40	0.30
	mhHR	.41	.04*	0.40
External load	mDEXP	.27	.20	0.24
	m1218	.18	.82	0.18
	m > 18	.29	.85	0.27
	ACCmax	.10	.44	0.00
	DECmax	.11	.33	0.00
	ACCavg	.40	.01*	0.38
	DECavg	.34	.01*	0.33
	mhACC	.29	.43	0.28
	mhDEC	.30	.29	0.28
	hIMP	.47	.39	0.45
Neuromuscular	hTOFF	.27	.69	0.25
	hLAND	.41	.69	0.39
	PL	.24	.21	0.21

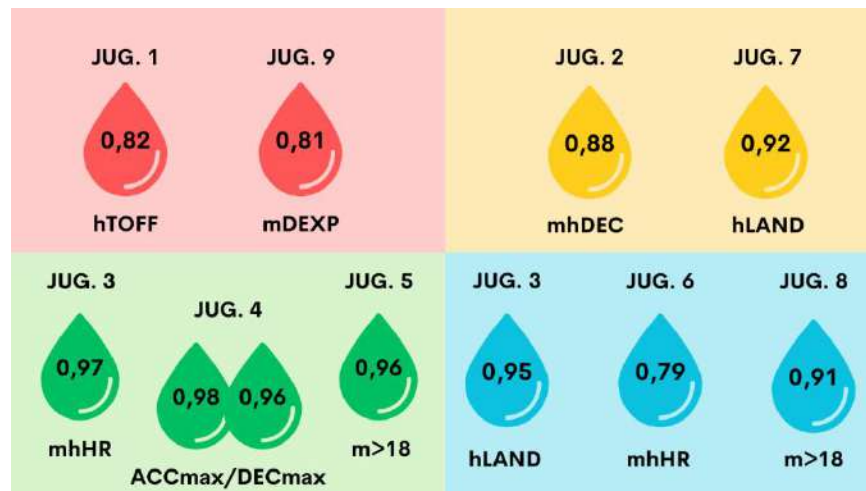
Note: Distance covered at > 1.12m/s² (mDEXP); Distance covered at 12-18km/h (m1218); Distance covered at over 18km/h (m > 18); Maximum acceleration (ACCmax); Maximum deceleration (DECmax); Average acceleration (ACCavg); Average deceleration (DECavg); Distance covered at > 3m/s² (mhACC); Distance covered at > -3m/s² (mhDEC); Maximum heart rate (HRmax); Average heart rate (HRavg); Distance covered at > 85% of maximum heart rate (mhHR); Impacts > 8G (hIMP); Take-offs > 3G (hTOFF); Landings > 5G (hLAND); Neuromuscular load (PL). Conditional R² values that are statistically significant, indicated by a p-value < .05 (*), have been highlighted in bold.

Table 6. Regression analysis results.

Variables		CV									
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Internal load	HRmax										
	HRavg										
	mhHR			0.97			0.79				
External load	mDEXP									0.81	
	m1218										
	m > 18					0.96			0.91		
	ACCmax				0.98						
	DECmax				0.96						
	ACCavg										
	DECavg										
	mhACC										
	mhDEC		0.88								
	hIMP										
Neuromuscular	hTOFF	0.82									0.82
	hLAND			0.95				0.92			
	PL										

Note: Distance covered at > 1.12m/s² (mDEXP); Distance covered at 12-18km/h (m1218); Distance covered at over 18km/h (m > 18); Maximum acceleration (ACCmax); Maximum deceleration (DECmax); Average acceleration (ACCavg); Average deceleration (DECavg); Distance covered at > 3m/s² (mhACC); Distance covered at > -3m/s² (mhDEC); Maximum heart rate (HRmax); Average heart rate (HRavg); Distance covered at > 85% of maximum heart rate (mhHR); Impacts > 8G (hIMP); Take-offs > 3G (hTOFF); Landings > 5G (hLAND); Neuromuscular load (PL). The menstrual cycle phase in which performance is superior is indicated by colours: Red: Menstrual; Yellow: Follicular; Green: Ovulation; Blue: Luteal. In colour: Variables where R² has proven to be significant for each player.

Following, in Figure 3, the significant results shown in the previous table are visually represented through a linear regression analysis.



Note: Distance covered at $> 1.12\text{m/s}^2$ (mDEXP); Distance covered at over 18km/h ($m > 18$); Maximum acceleration (ACCmax); Maximum deceleration (DECmax); Distance covered at $> -3\text{m/s}^2$ (mhDEC); Distance covered at $> 85\%$ of maximum heart rate (mhHR); Take-offs $> 3\text{G}$ (hTOFF); Landings $> 5\text{G}$ (hLAND). The menstrual cycle phase is indicated by colours: Red: Menstrual; Yellow: Follicular; Green: Ovulation; Blue: Luteal.

Figure 3. Variables where R² has proven to be significant for each player.

For instance, in the case of Player 1, 82% of the variability in take-offs above 3G can be explained by the menstrual cycle phase. Performance is significantly higher in the bleeding phase compared to the follicular phase. Regarding Player 2, 88% of the variability in distance covered at speeds greater than -3m/s^2 can be explained by the menstrual cycle phase. Performance is significantly higher in the follicular phase compared to the other phases. The menstrual cycle phase explains 97% of the variability in distance covered at over 85% of the maximum heart rate for Player 3, with significantly better performance in the ovulatory phase compared to the luteal phase.

DISCUSSION

The purpose of this research was to analyse the effects of the menstrual cycle on the variability of training load in female basketball players within the real training context, as well as to identify aspects to consider in the athletes' physical preparation. Therefore, it is crucial to understand which performance capacities are affected by players' biological conditions. Previous studies have indicated that performance may vary depending on the phase of the menstrual cycle, either improving or decreasing (Davis & Hackney, 2016; Grant et al., 2020; Ramos, 2022). The results of this study highlight the influence of the menstrual cycle phase on the variation of sports performance and the considerable hormonal variability at the individual level associated with this menstrual cycle. It has been observed that the menstrual cycle has an impact on sports performance (Kissow et al., 2022). Specifically, one would expect to find poorer results in the luteal phase and menstrual phase due to variations in hormones, including both progesterone and oestrogen (Marugán, 2019). The decrease in both hormones is likely responsible for this performance decline, indicating that the body is not prepared to reach its maximum level. On the other hand, in the follicular phase, hormone levels increase, preparing the body to face more intense loads. In fact, some studies have demonstrated significantly better performance in intermittent endurance and muscle strength during the follicular phase

compared to the luteal phase (Graja et al., 2022; Pallavi et al., 2017). Specifically, variables related to accelerations, decelerations, and explosive actions have been affected (Arenas-Pareja et al., 2023). These variables, along with jumps, are crucial in basketball performance (Hulka et al., 2014; Reina et al., 2019; Taylor et al., 2017).

Various studies have revealed that there is no clear trend for all female athletes in terms of sports performance during different phases of the menstrual cycle. Specifically, it has been found that performance was not affected by the menstrual cycle, but associated pains decreased during training and competition (Kishali et al., 2006). In another study, no trends were observed in performance when comparing the luteal and follicular phases. In fact, analysing days with and without menstruation, performance either increased or decreased (Tremback-Ball et al., 2021). Furthermore, when female athletes report their own sensations regarding performance during the menstrual cycle, 80% conclude that the menstrual cycle decreases performance in each cycle (Farage et al., 2009). On the other hand, some athletes, approximately 37%, perceive that they feel stronger, more motivated, and prepared to exert effort during the late follicular phase, ovulation (Michelekaki et al., 2023). In the present study, the various analysed variables exhibit different behaviours during the menstrual cycle both at the group level and individually.

The results of individuality through the MLM reveal variables with 0% individuality (HRmax, Accmax, Decmax) and variables with a great individual affectation, where the differences are explained by the different menstrual cycle in each subject by 35% or more (mhHR, Accavg, hIMP, hLand). These results indicate that for the variables of volume and neuromuscular intensity, each player will respond differently depending on the phase of the cycle in which she is, while the variables of maximum intensity are not affected by the differences between menstrual cycles of each player. Therefore, for a greater generalisation of training in team sports, the maximum values of internal load and kinematic external load should be observed. For a greater individualisation of the training load, the volume and maximum neuromuscular intensity variables should be observed.

Within the individual variability of athletes, the results show players who improve their performance in different phases of the menstrual cycle and even some who remain constant throughout the entire menstrual cycle. It is known that the duration of the menstrual cycle, the length of the phases, and the timing of the LH peak vary significantly among individuals. Additionally, ovulation and the peak of progesterone in the mid-luteal phase do not occur in every cycle for all women (Reed & Carr, 2000). The data obtained suggest that, to achieve the maximum performance of athletes, emphasis should be placed on the individuality of each team player, with the goal of building a personalized and effective training program that ensures optimal performance without compromising individual capacities or leading to excessive effort, as already suggested by McNulty et al. (2020).

The results of the present study reveal variations in intra-subject physical performance explained in more than 90% by the menstrual cycle in several female players, in variables such as falls, distance covered at high intensity and maximum accelerations and decelerations. Other studies (Gasperi et al., 2023) show how the menstrual cycle affects other essential components of basketball, such as technique and tactics, significantly. This results in greater irregularity in performance, which is evident in team sports such as basketball (Scanlan et al., 2012). Coaches should take into account the fluctuations in the menstrual cycle of their players when planning their weekly match schedule, bearing in mind that there may be occasional drops in the performance of players who are on a good trajectory.

The study presents a small sample due to the ecological nature of the study. Nevertheless, the results align with findings in the literature. Instead, the results indicate the need to focus on the individual aspect of the menstrual cycle (Laus, 2020), given the significant variability in players' outcomes. To achieve this, it is recommended to maintain a daily record allowing the adaptation of training sessions according to the phase of the menstrual cycle the player is in. In this way, it will be possible to understand how each phase affects performance and precisely adjust the training. In this context, it is interesting to establish a general structure for physical preparation considering the menstrual cycle of each player, following Bataller's proposal (Marugán, 2019). This would involve identifying, for each player, the most suitable moments for training focused on speed, explosiveness, strength, and maximum strength. Additionally, efforts would be made to measure peaks of maximum performance and adapt training to lower intensities during phases with reduced fatigue tolerance. During these periods, the recommendation is to focus on cardiovascular training within the range of the minimum effective volume and maximum adaptative volume. Another limitation is the lack of control for contaminant variables. The choice of ecological studies allows a closer approach to the real context, measuring and assessing what really happens in the sport, however, it makes you assume a greater influence of contaminating factors that require more robust statistical analyses to ensure that these contaminating variables do not influence, or influence as little as possible, the results found. This approach will make it easier for coaches to apply science in their training, as in day-to-day training it is impossible to isolate players from contaminating variables and they must live with these influences that condition behaviour, especially in experimental sciences with humans.

CONCLUSIONS

In summary, the findings of this research underscore the importance of considering the menstrual cycle in the planning and customization of training in women's basketball. The physical performance of players in relation to training load exhibited a significant level of variability, partly due to the menstrual cycle phase, which was considered a relevant variable in this study.

The integration of specific strategies based on menstrual cycle phases is a key factor for optimizing player performance by adjusting training loads, intensities, and approaches according to individual needs. For example, focus in the follicular phase on high intensity and explosive aspects; in the luteal phase on more tactical aspects with a lower physical load and the menstrual phase focusing on low impact exercises and active recovery. Also, during competitions the technical staff can take decisions about playing time of each player according to this information.

The individuality of each athlete is a key factor, as the response to the menstrual cycle can vary. It is therefore advisable a call to action to implement individualized menstrual cycle recordings in sports teams, supported by accessible technology such as mobile apps, to adapt training optimally, maximising performance during the most favourable phases and minimising the risk of fatigue in the less favourable ones.

Practical applications

Based on the findings of this study and the recommendations from the literature, it is possible to establish practical guidelines for adapting training sessions to the menstrual cycle phases, ensuring optimal performance and minimizing the risk of overtraining or injury. During the follicular phase, when hormonal levels, particularly oestrogen, are elevated, athletes may benefit from prioritizing high-intensity training focused on explosive actions, strength development, and speed. This phase is particularly suited for incorporating maximal strength training and plyometric exercises, given the body's enhanced tolerance to physical stress. In contrast, during the luteal phase and menstrual phase, when hormonal fluctuations,

especially increased progesterone and decreased oestrogen, can negatively affect performance and recovery, training loads should be adjusted accordingly. Coaches may focus on moderate-intensity cardiovascular exercises, technical skill development, and tactical sessions to maintain performance while reducing physical and psychological fatigue. Additionally, periods of intense pain or discomfort may call for further individualization, such as active recovery sessions or flexibility exercises. To implement these adaptations effectively, it is essential to maintain individual monitoring of each player's cycle and use this data to personalize training loads. Establishing this structure allows teams to enhance athletes' performance while addressing the physiological demands associated with their menstrual cycle.

As it is a team sport, it can sometimes be difficult to carry out sessions according to the menstrual cycle. If this is not possible, the ideal would be to adapt each player to the session. In particular, the players' rest periods can be modified, regulating the series in which each player takes part and modifying the rotations according to the players' needs. It is possible to prioritise the intervention of some players in certain tasks, participating more or less time in the tasks depending on whether they are more or less aerobic, with a greater or lesser impact load. Also, instead of grouping players by specific positions when training, groupings can be made according to training needs in certain high intensity tasks. The rest of the stimuli should be dealt with in the physical preparation or gym sessions, where each player can be individualised and it is easier to attend to the individual needs of each player.

In terms of competition, priority should be given to performance in those categories in which the players are already formed. To this end, sometimes it will not be possible to pay attention to the individuality of the players, but as far as possible with open scores in favour of the team, rotations established by the physical trainer after a load control must be respected in order to correctly manage the recovery periods necessary for a correct adaptation to the training and competition processes and to avoid overloads or risk of injury. In addition, training must also be adapted to what happens in competition. Those players with a deficit of playing time in competition, due to the coach's decision, will have to do compensatory sessions, attending to each of their needs. In other words, if in their phase they require a more power-focused load, they should compensate for the time not played with power-related activities. Therefore, this compensatory work should be modified weekly.

AUTHOR CONTRIBUTIONS

Conceptualization: M. d. I. A., P.L.S., S.J.I., J.G.R.; Data curation: M. d. I. A., J.G.R.; Formal analysis: M. d. I. A., J.G.R.; Funding acquisition: P.L.S., S.J.I., J.G.R.; Investigation: M. d. I. A., P.L.S.; Methodology: J.G.R.; Project administration: S.J.I., J.G.R.; Resources: S.J.I.; Software: S.J.I., J.G.R.; Supervision: J.G.R.; Validation: P.L.S., S.J.I.; Visualization: P.L.S.; Writing – original draft: M. d. I. A., J.G.R.; Writing – review & editing: P.L.S., S.J.I.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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Influence of gender and age on behavioral regulation in practitioners of group exercise activities

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ABSTRACT

Motivation plays a crucial psychological role in the participation and consistency of exercise and physical activities. Therefore, examining it in various types of directed activities (GEAs) can provide valuable resources for sports centres, enhancing the experience of their participants. The objective of the study was to analyse behavioural regulation in DA practitioners, exploring the relationships between their motivational variables and identifying differences in regulation based on gender, age, and type of GEA. A sample of 291 DA practitioners (64 men and 227 women) aged between 17 and 82 years (mean age: 42.79 ± 16.02 years) was used. The variables analysed were different types of behavioural regulation (using the BREQ-2 questionnaire). The results showed significant differences in behavioural regulation according to gender, age, and type of GEA. Men exhibited a greater tendency toward less self-determined regulation, those practicing body-mind GEAs (BM) showed higher levels of demotivation (DM), and younger participants demonstrated lower external regulation (ER). Further research is needed to confirm these findings.

Keywords: Motivation, Self-determination, Exercise, BREQ-2.

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INTRODUCTION

Group exercise activities (GEA) refer to structured forms of physical exercise conducted in a group setting under the guidance of an instructor who teaches, guides, and motivates participants (González-Cutre & Sicilia, 2012; Pérez-Villalba et al., 2017; Thompson, 2017). This exercise style represents a current trend in physical activity promotion (Box et al., 2019) and is frequently regarded as an effective intervention strategy to increase physical activity levels (Deforche & De Bourdeaudhuij, 2000; Nyström et al., 2016).

Different classifications of GEA exist due to the variety of training formats, which differ in aspects such as intensity, type, equipment used, and location (Mata, 2011). As highlighted by Hultquist (2012) and mentioned in Ginés-Díaz et al. (2021), GEA can be categorized into cardiorespiratory activities (CR) (e.g., aerobics or spinning), strength activities (SA) (those utilizing various resistances such as weights, bands, or body weight to build strength), mind-body activities (MB) (e.g., Pilates, stretching, or CORE classes), and specialized activities (SP) (such as salsa, belly dancing, hip-hop, etc.).

Motivation is defined as the result of various personal, social, and environmental factors that influence the choice of physical activity, the frequency and intensity of its practice, its persistence, and ultimately, performance (Escartí & Cervelló, 1994). Several theories have been developed to explain motivation as a key factor of human behaviour. However, all motivational differences related to physical exercise practice fall within the framework of self-determination theory (SDT) (Deci & Ryan, 1985, 1991, 2000), which has been extensively supported by research (Balaguer et al., 2008; Moreno, Cano et al., 2009; Ryan & Deci, 2000) and often combined with achievement goal theory (Nicholls, 1989).

Self-determination theory (Deci & Ryan, 1985, 1991, 2000) is a macro-theory of motivation that describes and explains how individuals can be intrinsically or extrinsically motivated to engage in activities. The theory structures motivation along a continuum, ranging from non-self-determined to self-determined behaviours, identifying three primary types of motivation: amotivation, extrinsic motivation, and intrinsic motivation. When basic psychological needs (autonomy, competence, and relatedness) are satisfied, individuals are more likely to feel intrinsically motivated to engage in an activity. This results in participation for the satisfaction it provides and greater freedom in decision-making. Conversely, if these needs are unmet, motivation becomes more extrinsic, driving individuals to participate for external reasons, which can lead to frustration or lack of interest (amotivation) (Moreno, Hernández & González-Cutre, 2009). Each form of motivation is associated with regulatory processes, which may include values, rewards, self-control, interests, enjoyment, satisfaction, and more (Moreno & Martínez, 2006).

Within the SDT framework, the organismic integration theory (OIT) (Ryan et al., 1985) provides further insight into how individuals internalize and integrate external regulations into their behaviour. This theory explores how the social environment can influence the adoption or rejection of cultural and social regulations. According to Ryan and Deci (2000), extrinsic motivation can take on various forms, depending on the degree of internalization and integration into behavioural regulation. Individuals may engage in activities due to external pressures (external regulation), feelings of guilt (introjected regulation), recognition of the activity's value without deriving pleasure from it (identified regulation), or because the activity aligns with their values and identity (integrated regulation). This continuum of behavioural regulation includes six stages: amotivation (AM), external regulation (ER), introjected regulation (IJR), identified regulation (IDR), integrated regulation (IGR), and intrinsic regulation (IR). These stages range from the least self-determined to the most self-determined behaviours.

Given that motivation is considered the most significant psychological factor influencing human behaviour (Iso-Ahola & Clair, 2000), its relationship with adherence to physical exercise is evident. As Schutzer and Graves (2004) assert, understanding adherence to exercise requires comprehending the specific cognitive processes associated with motivation. Therefore, the present study aims to enhance sports participation by examining the motivational factors influencing behavioural regulation in physical exercise and identifying preferences in this context based on factors such as the type of GEA, gender, and age of the participant. In line with the study's objectives, it is hypothesized that the highest intrinsic motivation scores will be observed among practitioners of CR-type GEA (Amate, 2020), older individuals (Muyor et al., 2009), and men (Castañeda et al., 2018), with men also scoring higher in IJR (Durán-Vinagre, 2022).

MATERIAL AND METHODS

Participants

The study sample initially included 303 participants; however, 12 were excluded as the physical activities they practiced could not be classified as a type of GEA, as they involved competitive sports (e.g., soccer, paddle tennis, running, etc.). As a result, the study was carried out with a final sample of 291 participants, aged between 17 and 82 years. Among these, 21.99% (N = 64) were men, while 78.01% (N = 227) were women. The mean age of the participants was 42.79 ± 16.02 years. Based on Erikson's (1968, 1993) classification of life stages, 5.50% (N = 16) were categorized as being in adolescence, 39.18% (N = 114) in early adulthood (EA), 41.92% (N = 122) in middle adulthood (MA), and 13.40% (N = 39) in late adulthood (LA).

In terms of the type of GEA practiced, 9.62% (N = 28) participated in cardiorespiratory activities (CR), 26.12% (N = 76) in mind-body activities (MB), 29.55% (N = 86) in strength activities (SA), 3.44% (N = 10) in specialized activities (SP), and 31.27% (N = 91) engaged in a combination of two or more of the aforementioned types, classified as multi-activity (MA).

Measures

BREQ-2

The Behavioural Regulation in Exercise Questionnaire-2 (BREQ-2) is one of the most widely used scales to measure behavioural regulation in exercise psychology research (Wilson, 2012). The original questionnaire (BREQ) was developed by Mullan et al. (1997) to measure IR, IDR, IJR, and ER. The second version of this questionnaire was created by Markland and Tobin (2004) and added a fifth factor to measure AM. The scale measures behavioural regulation in exercise based on 19 items, grouped into five factors: IR (e.g., "Because I enjoy exercise sessions"), IDR (e.g., "Because it is important to me to exercise regularly"), IJR (e.g., "Because I feel bad about myself if I don't exercise"), ER (e.g., "Because others tell me I should"), and AM (e.g., "I don't see the point in exercising"). Respondents answer the statement "I exercise..." through the items included in the scale. This study used the BREQ-2 version, which has shown significant factorial validity as well as validity in different contexts, validated for the Spanish context by Moreno, Cervelló, and Martínez (2007). The responses are closed-ended and follow a Likert scale from 1 to 5, where 1 means not true for me at all and 5 means completely true for me. Of the 19 items included in this scale, the Spanish validation by Moreno et al. (2007) discarded item 17 ("Because I get nervous if I don't exercise regularly") as it did not surpass the required saturation of 0.40. The internal consistency coefficients obtained during the Spanish validation of this questionnaire were as follows: IR, $\alpha = 0.89$; IDR, $\alpha = 0.81$; IJR, $\alpha = 0.82$; ER, $\alpha = 0.86$; AM, $\alpha = 0.89$. Therefore, these scales demonstrate adequate reliability ($\alpha > 0.70$) (Nunnally & Bernstein, 1994). Furthermore, the BREQ-2 has been used by Wang (2004) and Wilson and Rodgers (2004), both of whom

obtained adequate psychometric measures, demonstrating high factorial validity (Havnen et al., 2023) and reliability when applied in the Spanish context (Carcelén et al., 2023; Fuentes-García et al., 2021).

Procedures

This study employed a descriptive, cross-sectional design. Data collection was conducted through surveys using an online form. The digital survey was distributed via social media platforms and in various sports centres in Valencia, Spain, using an informational poster that provided access to the questionnaire. Participants were repeatedly informed that the form was voluntary and anonymous, in compliance with Royal Decree 3/2018, of December 5, on the Protection of Personal Data and the Guarantee of Digital Rights. The study adhered to the ethical principles outlined in the Declaration of Helsinki. Participants could clarify any doubts that arose at any time while completing the questionnaire. The average time required to complete the form was approximately 10 minutes. The survey began with a detailed explanation of the study, followed by a series of sociodemographic and contextual questions, and concluded with the single-selection questionnaire corresponding to the BREQ-2 measurement instrument. Participants were given two weeks from the date of distribution to complete the questionnaire.

Once the response period had ended, all collected responses were exported to Excel. The data regarding the type of GEA practiced by each participant were reorganized and grouped according to the classification proposed by Hultquist (2012), as referenced in Ginés-Díaz et al. (2021), with the addition of the multi-activity (MA) GEA category for participants who reported practicing more than two different types of GEA based on the employed classification. Following this reorganization, the grouping of surveyed GEAs was as follows:

Table 1. Grouping of surveyed GEAs based on the classification by Hultquist (2012).

Cardiorespiratory	Aerobics, spinning, Zumba, fit boxing, HIIT.
Strength	Personal training, CrossFit, Boompa, circuit training, body pump. GAP, functional training, weight training.
Mind-body	Pilates, yoga, CORE, body balance, maintenance gymnastics.
Specialized	Tai chi, hip-hop, dance.
Multi-activity	(Combination of at least two GEAs from different categories).

Note. GEA: Group Exercise Activities.

Additionally, participants were grouped into different stages based on their age. The age ranges for each period were defined using the classification of human developmental stages from Erikson's Psychosocial Development Theory (1968, 1993), with slight adjustments to the distribution due to the low number of participants in adolescence ($N = 16$) and their proximity to early adulthood (ages ranging from 17 to 20). Thus, individuals aged 17 to 40 were classified as early adulthood (EA), middle adulthood (MA) was defined as ages 41 to 60, and late adulthood (LA) included participants aged 61 and older.

Analysis

Inferential analysis of behavioural regulation variables was conducted based on the type of GEA, gender, and age using the Kruskal-Wallis test to examine differences between groups. Statistical significance was established at values less than .05. To identify which groups showed significant differences in motivational variables when comparing GEA types and age stages, both the types of GEA and age stages were compared using the Mann-Whitney U test with Bonferroni correction. Subsequently, Spearman correlation analysis was performed to explore the relationships among all dependent variables. Statistical significance was established at values less than .05.

Next, a reliability analysis was conducted to assess the internal consistency of the questionnaires used in the study. Cronbach's alpha was applied, with values equal to or greater than .70 indicating good consistency (Nunnally, 1978). Additionally, McDonald's omega coefficient was calculated to measure the internal consistency of the studied variables, as it is considered by many authors to provide greater accuracy. McDonald's omega ranges from 0 to 1, with values closer to 1 reflecting higher reliability in measurements (Revelle & Zinbarg, 2009). For the coefficient to be deemed adequate, it must exceed .70, which is interpreted as an acceptable level of confidence in the results (Campo-Arias & Oviedo, 2008).

RESULTS

Table 2 presents the descriptive values and internal consistency analysis of the five subscales of the BREQ-2. The results show that all five subscales demonstrate adequate internal consistency, with Cronbach's alpha and McDonald's omega values exceeding 0.70 for all variables. The IR subscale exhibits particularly high consistency, with alpha and omega values exceeding 0.90. The ER and IJR subscales also display high reliability, with coefficients above 0.80.

Table 2. Descriptive statistics and reliability analysis of the BREQ-2 subscales.

Variables	N	Minimum	Maximum	M	SD	α	ω
Intrinsic regulation	291	1.00	5.00	4.01	1.13	0.93	0.93
Identified regulation	291	1.00	5.00	3.78	1.45	0.75	0.81
Introjected regulation	291	1.00	5.00	2.26	1.29	0.83	0.83
External regulation	291	1.40	5.00	1.24	0.71	0.86	0.86
Amotivation	291	1.00	5.00	1.25	0.77	0.74	0.78

Note. M: Mean. SD: Standard deviation. α : Cronbach's alpha. ω : McDonald's omega.

Table 3 presents behavioural regulation variables according to the type of GEA practiced. Regardless of the activity, participants reported consistently high levels of IR and IDR, while reporting very low levels of ER and AM. Regarding group differences, significant differences were observed for AM based on the type of activity practiced ($H = 14.8$; $p < .01$; $\eta^2 = .04$). Specifically, pairwise comparisons revealed that participants practicing MB-type GEA reported higher AM ($Md = 1$; $IQR = 1.00-1.56$) than those practicing MA-type GEA ($Md = 1$; $IQR = 1.00-1.56$; $p < .05$), despite both groups having the same median. On the other hand, although differences were not significant, a trend was observed for IDR ($H = 7.94$; $p = .09$; $\eta^2 = .01$), indicating lower IDR among participants practicing SP-type GEA ($Md = 3.38$) compared to those practicing MA-type GEA ($Md = 4.00$; $p = .21$) and FZ-type GEA ($Md = 4.00$; $p = .29$).

Table 3. Behavioural regulation analysis by type of GEA.

Variable	Cardiorespiratory Md (IQR)	Mind-body Md (IQR)	Strength Md (IQR)	Specialized Md (IQR)	Multi-activity Md (IQR)	H	p	η^2
Intrinsic regulation	4.50 (3.44 – 5.00)	4.00 (3.25 – 4.75)	4.25 (3.06 – 5.00)	3.25 (2.81 – 4.88)	4.50 (3.75 – 5.00)	5.41	.20	.01
Identified regulation	4.00 (3.25 – 4.25)	4.00 (3.25 – 4.25)	4.00 (3.50 – 4.25)	3.38 (2.50 – 3.88)	4.00 (3.50 – 4.50)	7.94	.09	.01
Introjected regulation	2.33 (1.67 – 3.00)	2.33 (1.33 – 3.33)	2.00 (1.33 – 2.67)	1.50 (1.00 – 2.00)	2.00 (1.33 – 3.00)	6.67	.20	.01
External regulation	1.00 (1.00 – 1.25)	1.00 (1.00 – 1.25)	1.00 (1.00 – 1.00)	1.00 (1.00 – 1.50)	1.00 (1.00 – 1.13)	5.26	.30	.00
Amotivation	1.00 (1.00 – 1.56)	1.00 (1.00 – 1.56)	1.00 (1.00 – 1.00)	1.13 (1.00 – 1.44)	1.00 (1.00 – 1.00)	14.8	< .01	.04

Note. Md: Median; IQR: Interquartile Range.

In Table 4, behavioural regulation variables by gender are shown. Women tended to score slightly higher in more self-determined regulations such as IR (Md = 4.25) and IDR (Md = 4.00) compared to men (IR: Md = 4.00; IDR: Md = 3.75). However, neither IR ($p = .20$) nor IDR ($p = .80$) scores were statistically significant. Conversely, less self-determined regulation variables showed more significant results. Specifically, men scored slightly higher in ER (Md = 1; IQR = 1.00–1.50) and AM (Md = 1; IQR = 1.00–1.50) compared to women (ER: Md = 1; IQR = 1.00–1.00; AM: Md = 1; IQR = 1.00–1.00; $p < .05$). This suggests that, despite the small effect size ($\eta^2 = .01$), men tend to identify more with external regulation and amotivation statements (Table 4).

Table 4. Behavioural regulation analysis by gender.

Variable	Female Md (IQR)	Male Md (IQR)	H	p	η^2
Intrinsic regulation	4.25 (3.50 – 5.00)	4.00 (3.25 – 4.75)	1.60	.20	.00
Identified regulation	4.00 (3.31 – 4.25)	3.75 (3.50 – 4.25)	0.06	.80	.00
Introjected regulation	2.00 (1.33 – 3.00)	2.33 (1.67 – 3.00)	1.01	.30	.00
External regulation	1.00 (1.00 – 1.00)	1.00 (1.00 – 1.50)	4.36	<.05	.01
Amotivation	1.00 (1.00 – 1.00)	1.00 (1.00 – 1.50)	5.15	<.05	.01

Note. Md: Median; IQR: Interquartile Range.

In Table 5, behavioural regulation variables are shown based on age stage. The data indicate that scores decrease as the type of regulation becomes less self-determined. Additionally, significant differences were observed for ER ($H = 7.15$; $p = .03$; $\eta^2 = .02$). However, while pairwise comparisons did not reveal significant differences for ER, there is a clear trend of lower scores in early adulthood (EA) for this regulation type (Md = 1.00; IQR = 1.00–1.00) compared to middle adulthood (MA) (Md = 1.00; IQR = 1.00–1.25; $p = .06$) and late adulthood (LA) (Md = 1.00; IQR = 1.00–1.50; $p = .09$), despite similar medians across all three age stages.

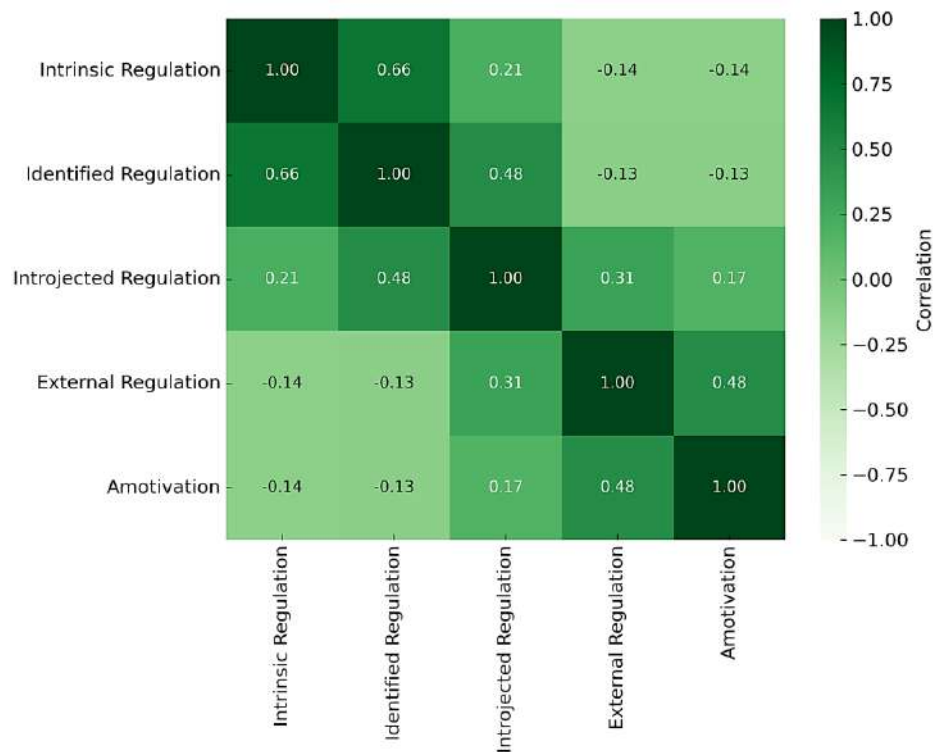


Figure 1. Correlations between behavioural regulation variables.

Table 5. Behavioural regulation analysis by age stage.

Variable	Early adulthood Md (IQR)	Middle adulthood Md (IQR)	Late adulthood Md (IQR)	H	p	η^2
Intrinsic regulation	4.50 (3.50 – 5.00)	4.25 (3.25 – 5.00)	4.12 (3.25 – 5.00)	0.74	.70	.00
Identified regulation	4.00 (3.25 – 4.25)	4.00 (3.50 – 4.25)	4.00 (3.44 – 4.50)	0.56	.80	– .01
Introjected regulation	2.00 (1.33 – 2.75)	2.00 (1.33 – 3.00)	2.17 (1.00 – 3.00)	0.89	.60	.00
External regulation	1.00 (1.00 – 1.00)	1.00 (1.00 – 1.25)	1.00 (1.00 – 1.50)	7.15	<.05	.02
Amotivation	1.00 (1.00 – 1.00)	1.00 (1.00 – 1.38)	1.00 (1.00 – 1.25)	2.16	.30	.00

Note. Md: Median; IQR: Interquartile Range.

Figure 1 illustrates the relationships between all variables. The strongest positive correlation is observed between IR and IDR ($r = 0.66$). Additionally, weaker correlations are noted between IDR and IJR ($r = 0.48$), as well as between ER and AM ($r = 0.48$).

DISCUSSION

The results obtained in this study reveal certain significant aspects that require analysis and comparison with similar research to validate or refute the proposed hypotheses.

Before discussing the findings based on the established objectives, it is important to highlight one of the most notable sociodemographic aspects of the data collected in this study: the clear predominance of female participants (78.01% women compared to 21.99% men). This finding aligns with other studies that observe a greater prevalence of women participating in GEAs compared to men. Specifically, Tuero and González-Boto (2018) observed a similar trend in the context of aquatic activities, where women showed a greater preference for participating in aquatic GEAs (69.5% of respondents) compared to men (51.4% of respondents). In this regard, it is essential to highlight the influence of the type of activity, as the results of a study that also employed the BREQ-2 in the Spanish context indicated that women revealed more positive motivation than men in aquatic activities, whereas no gender differences were found in terrestrial activities (Moreno et al., 2009). Similarly, a study that used the BREQ-2 to examine the influence of gender and physical activity on motivation among Spanish children aged 12 to 15 years (Varela, 2010) found that boys were more active than girls, which translated into higher motivation for physical activity—potentially influenced by age.

As expected, participants scored higher on the more self-determined behavioural regulation variables (IR and IDR) and lower on the less self-determined variables (ER and AM). These results are similar to those presented by Durán-Vinagre (2022) and align with the current literature, which indicates that more self-determined forms of regulation lead to greater engagement in physical activity, with intrinsic motivation being the most predictive of long-term adherence (Teixeira et al., 2012). This relationship is further evidenced in the correlation analysis, which found strong relationships between the more self-determined variables, such as IR and IDR ($r_s = 0.66$), and weaker relationships between the less self-determined variables, such as ER and AM ($r_s = 0.48$).

Regarding differences in behavioural regulation based on the type of GEA practiced, significant differences were observed only in AM. Specifically, participants practicing MB-type GEAs reported higher AM than those practicing MA-type GEAs. This may suggest that individuals who engage in various types of GEAs simultaneously have more self-determined behaviour, possibly due to their enjoyment of physical exercise itself, regardless of the type of GEA. Additionally, Amate (2020) observed in their study that CR-type activities scored higher in intrinsic motivation, consistent with the hypotheses and the present analysis, where CR and

MA-type GEAs achieved the highest scores in this level of behavioural regulation. However, these differences were not statistically significant ($p > .05$).

In terms of gender-based differences in behavioural regulation, Özdilek et al. (2016) indicate that motivation for sports differs according to this sociodemographic variable. In line with this, our study observed differences in IR ($p = .20$) and IDR ($p = .80$) that were not statistically significant. These differences highlight slightly higher scores among women in these more self-determined stages of behavioural regulation. The significant differences ($p < .05$) indicate higher RIQ scores for men in the less self-determined stages of behavioural regulation (ER and AM). This suggests more self-determined behaviour among women and less self-determined behaviour among men. These findings align with those of various authors (Fuhrmann, 2018; Jakobsen & Evjen, 2018), who state that women exhibit higher intrinsic motivation for physical exercise, while extrinsic factors are more prevalent among men. However, these results contradict both the hypothesis and findings from other studies, which highlight that men display higher intrinsic motivation than women (Durán-Vinagre, 2022; Castañeda et al., 2018; Concha et al., 2017). Conversely, Muyor et al. (2009) found no significant differences in behavioural regulation related to gender. Additionally, although not statistically significant ($p = .30$), men scored slightly higher in IJR than women. This finding is consistent with the hypothesis and Durán-Vinagre's (2022) results, which were statistically significant in this aspect.

In relation to age-based differences in behavioural regulation, the results show significant differences only in ER, which was more prevalent among middle-aged and older adults. This finding is associated with more self-determined behaviour among younger participants. These results contradict the hypothesis based on findings by Muyor et al. (2009), which indicated higher values for more self-determined regulations among older age groups. However, Brunet and Sabiston (2011) found that middle-aged adults (in their study, aged 45 to 64 years) exhibited lower intrinsic motivation compared to younger adults, indirectly aligning with the results obtained here.

One of the main limitations of this analysis lies in the need, as stated by Sansone and Harackiewicz (2000), to examine motivational patterns among individuals in similar environmental contexts. Therefore, future studies could explore how various variables affect motivational factors in similar settings, such as gyms, specialized centres, or personal classes. Additionally, since this study considered different age groups ($M = 42.79 \pm 16.02$), it encompassed a wide range, implying that the results may not be entirely significant when compared with more homogeneous populations, such as students (Fuhrmann, 2018; Jakobsen & Evjen, 2018; Durán-Vinagre, 2022; Fernández-Ozcotta et al., 2015). A potential focus for future research could involve analysing disparities in motivational factors for different types of GEAs within the same age group—for example, among older adults. This group is particularly relevant, as Deforche and De Bourdeaudhuij (2000) suggest that organized and structured physical activities offer greater opportunities for older individuals to remain physically active. Due to the cross-sectional design of this study, it is not possible to establish causal relationships between the analysed variables. Future research could address this limitation by observing how different types of GEAs influence motivational factors before and after their implementation.

CONCLUSIONS

Men showed a slightly higher predisposition toward less self-determined regulation. In this line, individuals practicing MB-type GEAs reported slightly higher AM compared to the rest. Similarly, younger participants exhibited lower ER compared to middle-aged and older adults.

Further research in this field is required. Considering the limitations identified in this analysis, future studies should focus on examining similar environments and contexts (such as gyms or sports centres), utilizing more homogeneous population samples in terms of age (e.g., students or older adults), and striving to determine causal relationships through the implementation of longitudinal studies.

AUTHOR CONTRIBUTIONS

Fernando Picó contributed to data collection, data analysis, and the writing and revision of the manuscript. Rafael Martínez-Gallego contributed to the study design, data analysis, and the writing and revision of the manuscript. Juan Pedro Fuentes contributed to data analysis and the writing and revision of the manuscript.

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Physiological responses to HIIT: Enhancing aerobic capacity alongside anaerobic power

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ABSTRACT

Aim: This study was accomplished to find out the effects of HIIT on both anaerobic and aerobic capacities separately. **Method:** Twenty-four healthy individuals between the ages of 18 and 25 participated voluntarily in this study. The volunteers took part in the study were split into two distinct groups as control group ($n = 14$) and experimental group ($n = 10$). A HIIT program, comprised of a single 90-minute session, three days a week was applied to the experimental group for a time period of 8 weeks. The control group, on the other hand, had no exercise intervention and they were instructed to pursue their daily life activities. Before exercises and after training program, the levels of height, body weight, body fat percentage, VO_{2max} , ventilatory threshold, respiratory compensation point, and anaerobic power of both groups were detected as required. **Results:** After relevant training program, a significant increase was observed in the experimental group in terms of the levels of maximum power (w/kg) and average power (w/kg) from Wingate anaerobic testing ($p < .05$). In addition, a significant increase was also observed in VO_{2max} (ml/kg/min) and respiratory compensation point VO_2 (ml/kg/min) values ($p < .05$). **Conclusion:** The results obtained hereby indicate that the practices of HIIT are effective particularly on anaerobic performance, but they also increase the aerobic performance. Employing the high-intensity interval training may be, therefore, beneficial for the athletes who do not have adequate training time as well as for the athletes who desire to reduce the duration and scope of training without experiencing any loss in VO_{2max} and performance levels during the pre-competition period. Furthermore, due to its favourable effects on cardiovascular health resulted from the increases in VO_{2max} , the high-intensity interval training also can be used in exercises of sedentary individuals, paying particular attention to the principles of loading.

Keywords: Cardiopulmonary exercise testing, Wingate anaerobic testing, Athletic performance.

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INTRODUCTION

Aerobic and anaerobic capacity are determining factors for energy utilization and athletic success in daily activities of individuals (McArdle et al., 2015). Aerobic capacity characterizes the efficiency of oxygen-utilizing systems, while anaerobic capacity refers to the efficiency of oxygen-free energy production processes (Brooks et al., 2005). Improving these two capacities plays crucial role in building up athletic performance (McArdle et al., 2015).

Endurance training are applied as a fundamental technique for augmenting the aerobic capacity. Endurance trainings are comprised essentially of aerobic activities that are exercised for a prolonged and at moderate-intensity (Bassett et al., 2000). Relevant training activities increase cardiac output, letting more blood to be circulated, support mitochondrial biogenesis in skeletal muscles, and increase the activities of oxidative enzymes. Aforesaid processes increase the aerobic metabolic capacity and as a result, significant surges are observed in VO_2max levels (Bassett et al., 2000).

The high-intensity interval training, on the other hand, intensely stimulates the anaerobic energy systems in muscles, contributing to the improvement of maximum power production, lactate buffering capacity, and anaerobic endurance (Laursen et al., 2002). It was noted, meanwhile, that the high-intensity interval training is also reported to promote central and peripheral adaptations for aerobic performance, such as mitochondrial biogenesis, increased oxidative enzyme activity, and capillary density (Gibala et al., 2006). Gibala et al. (2006) reported in their study that a protocol of short-term high-intensity interval training employed for a period of only two weeks provided significant increases in VO_2max levels (Gibala et al., 2006). Burgomaster et al. (2008) declared, meanwhile, that the high-intensity interval training program implemented three days a week for a period of six weeks improved oxidative capacity that contributing to the aerobic energy system, and the muscle biopsy data promoted relevant results (Burgomaster et al., 2008).

The high-intensity interval training is an exercise protocol in which short periods of high-intensity exercises and low-intensity recovery periods are consecutively repeated, unlike moderate-intensity aerobic activities (Thum et al., 2017). During exercises, each session ranges between 15 seconds and 4 minutes and aims to reach 80% to 95% of an athlete's maximum heart rate. Recovery time is typically equal to or slightly longer than the intense training interval and is realized through passive rest or low-intense exercises at 40% to 50% of maximum heart rate (Bayati et al., 2011). The high-intensity interval training has been attracting attention as an alternative to the traditional prolonged endurance exercises in recent years (Buchheit et al., 2013).

Fundamental objective of this study was to put forth the level of effectiveness of high-intensity interval training on both aerobic and anaerobic energy systems. This study was conducted herewith to assess the effects on both capacities individually, implementing only the high-intensity interval protocol.

METHODS

Participants and experimental design

Before starting the study, approval needed was obtained from the Sivas Cumhuriyet University Non-Interventional Clinical Research Ethics Committee dated December 14, 2022, with the decision number 2022-12/26. Twenty-four healthy individuals between the ages of 18 and 25 took part in the study as voluntary. Some specific incorporation criteria were applied to in selection of volunteers in order to minimize external variables that might affect relevant levels of physical fitness. In this regard, the participants were required to have not taken part in any regular physical activity in the last 12 months, not to have any

diagnosed chronic disease, and not to be under any ongoing pharmacological treatment. The volunteers participated in the study were separated into two categories namely as control group ($n = 14$) and experimental group ($n = 10$). The volunteers of experimental group were subjected to the high-intensity interval training program consisting, as detailed below, of a single unit 90-minute sessions lasting 3 days a week for a time period of total 8 weeks. The volunteers of control group, on the other hand, received no exercise and were allowed to pursue their routine life activities. Before starting the study, the levels of height, weight, body fat percentage, maximal oxygen consumption capacity ($\text{VO}_{2\text{max}}$), ventilatory threshold, respiratory compensation point, and anaerobic power of both groups were settled as required. After the high-intensity interval training program applied to the experimental group for 8 weeks, the measurements aforespecified were taken again from both groups.

Height and body weight measurement

Body weights of the volunteers took part in the study were measured using a brand Tanita BIA device with an accuracy of 0.1 kg, while they were barefoot and wearing only shorts. Their heights were measured by means of a tape measure with a sensitivity of 0.1 cm, while they were barefoot.

Body fat percentage measurement

Body fat percentages were measured using a brand TANITA Body Composition Analyzer. Before taking measurements needed, the volunteers were instructed not to eat anything for at least 4 hours, not to consume any beverages, including alcohol and caffeine-containing drinks, for at least 4 hours, not to enter saunas or take bath and to avoid physical activities during the day. During the measurements, the volunteers were instructed to stand barefoot on metal surface of the device, grasp handles of the device with both hands, and spread their arms parallel to their bodies. The data collected by the device throughout the measurement were recorded accordingly.

Maximal oxygen consumption test

A Maximal Exercise Test was accomplished on the treadmill to detect the levels of maximum oxygen consumption of the volunteers. Throughout the test, the gas exchange measurements of the volunteers were recorded by means of a Quark CPET gas analyser. The test was performed on a treadmill with an inclination of 0% and a starting speed of 7 km.h^{-1} . Then, the speed was increased by 1 km.h^{-1} every minute, allowing the volunteers to keep exercising till exhaustion. The aspects basically as volunteers' achievement the maximal heart rate during the test, the respiratory exchange ratio (RER), which is the instantaneous ratio of carbon dioxide (VCO_2) and oxygen intake (VO_2) measured during expiration, reaching the levels higher than 1.10, and oxygen intake remaining constant despite increasing exercise intensity were all taken into account as the criteria for reaching $\text{VO}_{2\text{max}}$ (Poole et al., 2017). The highest 15-second oxygen uptake value, in which at least two of these criteria occurred simultaneously, was accepted as $\text{VO}_{2\text{max}}$ (ml.kg.min^{-1}). Exhaustion time was determined herewith as the total duration of the test.

Determination of ventilatory threshold and respiratory compensation point

The values of volunteers' ventilatory threshold were determined by means of the non-invasive V-Slope method during a treadmill Maximal Exercise Test (Beaver et al., 2016). The position of the VO_2 curve associated with VCO_2 is examined in accordance with this procedure. When relevant exercise is initiated, VCO_2 and VO_2 increase proportionally to each other, resulting with a slope of the curve representing the correlation between VCO_2 and VO_2 that is approximately equal to 1. However, when a certain level of exercise is reached, the correlation between VCO_2 and VO_2 begins to exhibit a steeper slope due to the nonmetabolic CO_2 released as a result of buffering of lactic acid-derived hydrogen ions accumulated with bicarbonate in addition to the CO_2 produced by aerobic metabolism. After plotting the VCO_2 (y-axis) curve corresponding to

VO₂ (x-axis), two regression lines with a slope equal to (or closest to) 1 and higher than 1 are generated by carrying out the linear regression analysis. The point of intersection of these two regression lines is taken into account as the ventilatory threshold. VO₂ (ml.kg.min⁻¹) value corresponding to the ventilatory threshold point, heart rate, and running speed (km.h⁻¹) are determined at this point. While the VE/VCO₂ ratio begins to increase when assessing the respiratory compensation point, the point at which PETCO₂ level begins to decrease is appointed as the respiratory compensation point. The levels of VO₂ (ml.kg.min⁻¹), heart rate, and running speed (km.h⁻¹) corresponding to the respiratory compensation point are settled accordingly (Hirakoba et al., 2002).

Determining anaerobic power levels

Anaerobic power levels of the volunteers were measured using the 30-second Wingate Anaerobic Test. After adjusting the resistance value on the ergometer to 75 g/kg, the volunteers were instructed to pedal as fast as possible for 30 seconds. The pedal counter recorded the relevant data every 5 seconds throughout the test. When the test was completed, the first 5 seconds of the data collected were taken into account as alactastic capacity and the remaining time was considered as lactacid capacity (Haff et al., 2022). After the test, the values of maximum power (W/kg), minimum power (W/kg), average power (W/kg), and power drop (%) were recorded accordingly.

Table 1. Contents of the high intensity interval training protocol.

Week	Session	Sets	Repetitions × Distance (m)		
1	1	1	5 x 20m sprint		
	2	1	5 x 20m sprint		
	3	1	5 x 20m sprint		
	4	2	5 x 20m sprint	5 x 20m sprint	
2	5	2	5 x 20m sprint	5 x 20m sprint	
	6	2	5 x 20m sprint	5 x 20m sprint	
	7	2	5x 20m sprint	5x 40m sprint	
3	8	2	5x 20m sprint	5x 40m sprint	
	9	2	5x 20m sprint	5x 40m sprint	
	10	2	5x 20m sprint	5x 40m sprint	
4	11	2	5x 20m sprint	5x 40m sprint	
	12	2	5x 20m sprint	5x 40m sprint	
	13	3	5x 20m sprint	5x 40m sprint	5x 60m sprint
5	14	3	5x 20m sprint	5x 40m sprint	5x 60m sprint
	15	3	5x 20m sprint	5x 40m sprint	5x 60m sprint
	16	3	5x 20m sprint	5x 40m sprint	5x 60m sprint
6	17	3	5x 20m sprint	5x 40m sprint	5x 60m sprint
	18	3	5x 20m sprint	5x 40m sprint	5x 60m sprint
	19	3	5x 20m sprint	5x 40m sprint	5x 60m sprint
7	20	3	5x 20m sprint	5x 40m sprint	5x 60m sprint
	21	3	5x 20m sprint	5x 40m sprint	5x 60m sprint
	22	3	5x 20m sprint	5x 40m sprint	5x 60m sprint
8	23	3	5x 20m sprint	5x 40m sprint	5x 60m sprint
	24	3	5x 20m sprint	5x 40m sprint	5x 60m sprint

Training protocol

The high-intensity interval training was applied only to the experimental group, three days a week for eight weeks, with a single unit of 90-minute training session. Before starting the exercises, the volunteers accomplished a 20-minute warm-up, a 50-minute high-intensity interval training session, and finally a 20-

minute cool-down. In the high-intensity interval training protocol applied, the first week covered a single set of 5x20m sprint runs; the second week two sets of 5x20m sprint runs; the third week the first set of 5x20m and the second set of 5x40m sprint runs; the fourth week the first set of 5x20m and the second set of 5x40m sprint runs, and the fifth, sixth, seventh, and eighth weeks the first set of 5x20m, the second set of 5x40m, and the third set of 5x60m sprint runs. The contents of high-intensity interval training program applied were presented in Table 1.

Statistical analysis

Initially, descriptive statistics of the data collected in the study were realized as required. Then, Shapiro-Wilk test, skewness, kurtosis, histogram, Q-Q, and P-P graphs were utilized to find out whether the data were normally distributed. Since the data indicated normal distribution, Paired-Samples T-Test was conducted to compare the values of both pre-training and post-training. The significance level was accepted as $p < .05$.

RESULTS

Age and height (cm) values of the volunteers took part in the study were given in Table 2.

Table 2. Descriptive information of volunteer groups.

	Experimental Group (n = 14)			Control Group (n = 10)		
	$\bar{X} \pm SD$	Min.	Max.	$\bar{X} \pm SD$	Min.	Max.
Age (Years)	21.71 $\pm$ 1.77	19	25	20.80 $\pm$ 1.55	19	23
Height (cm)	180.43 $\pm$ 5.43	172	192	177.60 $\pm$ 7.09	168	188

The results of body weight (kg) and body mass index (kg/m²) measurements the volunteer group were given in Table 3. The measurements revealed no significant difference both before and after the training program for both groups ($p > .05$).

Table 3. Body weight and body mass index measurement results of volunteer groups (n = 14).

		Pre-Training	Post-Training	t	p
		$\bar{X} \pm SD$	$\bar{X} \pm SD$		
Experimental group	Body Weight (kg)	72.42 $\pm$ 7.47	72.58 $\pm$ 7.76	-0.513	.619
	BKI (kg/m ²)	22.47 $\pm$ 1.84	22.52 $\pm$ 1.99	-0.559	.588
Control group	Body Weight (kg)	68.02 $\pm$ 9.36	68.54 $\pm$ 9.35	-1.288	.230
	BKI (kg/m ²)	21.63 $\pm$ 3.38	21.10 $\pm$ 3.58	1.619	.140

Wingate test results of the experimental group were submitted in Table 4. Accordingly, a significant increase was observed in maximum power (w/kg) and average power (w/kg) values of the experimental group after the training program ($p < .05$). On the other hand, there was no significant difference in the values of minimum power (w/kg) and power drop (%) ($p > .05$).

Table 4. Wingate anaerobic test results of the experimental group (n = 14).

	Pre-Training	Post-Training	t	p
	$\bar{X} \pm SD$	$\bar{X} \pm SD$		
Maximum power (w/kg)	13.12 $\pm$ 1.37	14.13 $\pm$ 1.51	-4.094	.002*
Average power (w/kg)	8.53 $\pm$ 0.49	8.78 $\pm$ 0.44	-4.113	.002*
Minimum power (w/kg)	4.88 $\pm$ 0.62	4.96 $\pm$ 0.55	-0.472	.647
Power drop (%)	62.21 $\pm$ 7.13	64.42 $\pm$ 6.03	-1.491	.167

Note. * $p < .05$.

Wingate anaerobic test results of the control group were given in Table 5. No significant difference was obtained between the Wingate test results of the control group both before and after the training program ($p > .05$).

Table 5. Wingate anaerobic test results of the control group (n = 10).

	Pre-Training	Post-Training	t	p
	$\bar{X} \pm SD$	$\bar{X} \pm SD$		
Maximum power (w/kg)	13.02 $\pm$ 1.85	13.11 $\pm$ 1.81	-1.011	.339
Average power (w/kg)	8.54 $\pm$ 0.87	8.69 $\pm$ 1.09	-1.083	.307
Minimum power (w/kg)	8.54 $\pm$ 0.87	8.69 $\pm$ 1.09	-1.083	.307
Power drop (%)	65.77 $\pm$ 7.88	65.29 $\pm$ 7.33	1.692	.125

The cardiopulmonary results for the experimental group were presented in Table 6. After the training program applied to the experimental group, a significant increase was observed in the values of VO_{2max} (ml.kg.min⁻¹) and Respiratory Compensation Point VO_2 (ml.kg.min⁻¹) ($p < .05$). The study revealed no significant difference in other cardiopulmonary test results ($p > .05$).

Table 6. Cardiopulmonary measurement results of experimental group (n = 14).

	Pre-Training	Post-Training	t	p
	$\bar{X} \pm SD$	$\bar{X} \pm SD$		
VO_{2max} (ml/kg/min)	48.55 $\pm$ 4.48	53.27 $\pm$ 5.12	-3.131	.011*
Ventilatory threshold VO_2 (ml/kg/min)	43.13 $\pm$ 6.94	44.85 $\pm$ 3.10	-0.780	.453
Respiratory compensation point VO_2 (ml/kg/min)	47.85 $\pm$ 5.57	52.74 $\pm$ 4.73	-3.172	.010*
Ventilatory threshold time (min)	6.25 $\pm$ 1.84	6.05 $\pm$ 1.44	0.276	.788
Respiratory compensation time (min)	8.24 $\pm$ 1.89	8.84 $\pm$ 1.89	-1.291	.226
Maximum speed (km/h)	16.45 $\pm$ 1.86	16.54 $\pm$ 1.91	-0.219	.831
Ventilatory threshold speed (km/h)	12.90 $\pm$ 1.81	12.81 $\pm$ 1.40	0.126	.902
Respiratory compensation speed (km/h)	14.81 $\pm$ 1.94	15.45 $\pm$ 1.91	-1.295	.224
Exhaustion time (min)	9.98 $\pm$ 1.96	9.96 $\pm$ 2.03	0.033	.974

Note. * $p < .05$.

Cardiopulmonary measurement results of the control group were given in Table 7 above. When the data acquired were examined, no significant difference was observed between the results of cardiopulmonary test measurements of the control group both before and after the training program ($p > .05$).

Table 7. Cardiopulmonary measurement results of control group (n = 10).

	Pre-Training	Post-Training	t	p
	$\bar{X} \pm SD$	$\bar{X} \pm SD$		
VO_{2max} (ml/kg/min)	48.21 $\pm$ 5.93	48.23 $\pm$ 5.71	-0.106	.918
Ventilatory threshold VO_2 (ml/kg/min)	41.41 $\pm$ 4.19	41.52 $\pm$ 4.13	-0.670	.520
Respiratory compensation point VO_2 (ml/kg/min)	46.92 $\pm$ 5.82	46.45 $\pm$ 5.43	1.483	.172
Ventilatory threshold time (min)	4.36 $\pm$ 0.94	4.42 $\pm$ 0.92	-0.701	.501
Respiratory compensation time (min)	6.24 $\pm$ 1.28	6.33 $\pm$ 1.12	-0.804	.442
Maximum speed (km/h)	14.00 $\pm$ 1.49	14.20 $\pm$ 1.13	-1.500	.168
Ventilatory threshold speed (km/h)	11.20 $\pm$ 1.03	11.40 $\pm$ 0.96	-1.500	.168
Respiratory compensation speed (km/h)	13.00 $\pm$ 1.33	13.10 $\pm$ 1.19	-1.00	.343
Exhaustion time (min)	7.35 $\pm$ 1.51	7.60 $\pm$ 1.48	-1.530	.160

DISCUSSION

Athletes take advantage of miscellaneous training techniques to heighten their aerobic and anaerobic capacities. While the prolonged low-to-moderate-intensity exercises that enhance aerobic performance increase the endurance capacity, the high-intensity short exercises that improve anaerobic performance upgrade the explosive strength and speed. It's remarkable, meanwhile, that the high-intensity interval training, applied to improve anaerobic performance, also have efficacious outcomes on aerobic capacity.

Boosting the aerobic capacity requires a long period of time. For an aerobic exercise program to be effective enough, it is advised that each session last at least 45 to 50 minutes and be practiced at least three times a week. This type of endurance training should be sustained for 8 to 12 weeks to achieve prominent improvement. It has been reported, however, that incorporating the high-intensity interval training practices into aerobic training can speed up the adaptation process, support aerobic capacity development, and significantly reduce the time to reach the aerobic capacity aimed (Akgül et al., 2017).

This study revealed no statistically significant difference in body weight and body mass index values of the experimental group after the training program ($p > .05$). Likewise, the study revealed no statistically significant difference in terms of body weight and body mass index values of the control group ($p > .05$). The high-intensity interval training practices cover generally the short-duration, but intense exercises. While these protocols are effective for improving the aerobic and anaerobic capacities, they may not make up a total energy deficit long enough to cause changes in body weight and body mass index (Gibala et al., 2008; Keating et al., 2017). Similar to the results collected in our study, McMillan et al. (2005) conducted a 10-week high-intensity interval training program together with 11 young footballer, exercising twice a week at 90-95% of HRmax and observed no statistically significant change in body mass index levels (McMillan et al., 2005). It was set forth in another study that the high-intensity interval training performed regularly three days a week for a period of eight weeks did not lead to any significant change in the values of body weight and body mass index (Yüksel et al., 2007).

When the Wingate anaerobic test results of the experimental group were analysed, a significant increase was found out in terms of maximum power (W/kg) and average power (W/kg) values collected after the training program ($p < .05$). The study revealed no statistically significant dissimilarity in the values of minimum power (W/kg) and power drop (%) ($p > .05$). No significant difference was observed in the Wingate anaerobic test results of the control group both prior to and after the training program ($p > .05$).

It has been detected that the high-intensity interval training protocol provides increases on the anaerobic performance by leading to significant changes in terms of maximum power (W/kg) and average power (W/kg) values of the Wingate test results. Such an increase observed in the anaerobic performance may be resulted from several reasons. First, the high-intensity interval training effectively stimulate and contribute to improve the glycolytic energy pathway. This process can assist in maintaining power production throughout the Wingate test by increasing lactate production and the muscles' ability to buffer the lactate (MacInnis et al., 2017). In addition, high-intensity interval trainings primarily target the fast-twitch (type II) muscle fibres. Relevant fibres can contribute to, with their talents to produce high force and speed, maximum and average power to be increased in the Wingate test (Tillin et al., 2009).

A study accomplished by MacDougall et al. (1998) reported a significant increase, in parallel with the results in our study, in terms of maximum power and average power values of the Wingate test results of volunteers after applying the high-intensity interval training protocol consisting of 30 seconds of loading and 2.5 to 4

minutes of resting intervals for a time period of 7 weeks (Macdougall et al., 1998). Another study carried out by Rodas et al.(2000), revealed that a 2-week high-intensity interval training protocol comprised of 15 seconds of loading and 45 seconds of resting resulted with a significant increase in the activities of phosphocreatine, glycogen, and anaerobic enzymes (Rodas et al., 2000). Xu and Wang (2025) reported a significant increase in the values of maximum power and average power from Wingate test results after 10 weeks of sprint interval training applied to karate athletes (Xu et al., 2025).

On the other hand, when the results of cardiopulmonary test, which reflects the aerobic performance, were examined, it was determined that the high-intensity interval training program applied resulted with a significant increase in VO_{2max} values of the experimental group ($p < .05$). No significant difference was observed, as expected, in the VO_{2max} values of the control group ($p > .05$).

Favourable effects of high-intensity interval training on VO_{2max} can be expressed by both central (cardiovascular) and peripheral (muscular) physiological adaptations (Buchheit et al., 2013; MacInnis et al., 2017). High-intensity interval trainings allow the heart muscles to contract more powerful and pump more blood (Laursen et al., 2002). Such an attitude leads to increased stroke volume at rest and during exercise, therefore, transferring more oxygen to the tissues and as a result elevating the level of VO_{2max} (MacInnis et al., 2017). Moreover, the high-intensity interval training leads to an increase in left ventricular wall and volume, allowing more blood to be pumped during exercises (Gibala et al., 2012). All of the aforesaid results increase cardiac output and thus amplify the conveyance capacity of circulatory system (MacInnis et al., 2017). Furthermore, it is noted that the high-intensity interval training stimulates some of the similar molecular signalling pathways that arrange the skeletal muscles to be remodelled in response to the endurance training, including transfer of carbohydrates and fats, and changes in the oxidation capacity in combination with mitochondrial biogenesis (Kenney et al., 2022). It is considered that the significant increase observed in VO_{2max} level in this study is due to the reasons aforespecified.

The level of anaerobic threshold is another aspect that influences the endurance performance (Coates et al., 2023). The athletes who reach the anaerobic threshold later have higher endurance capacities (Heuberger et al., 2018). Anaerobic threshold can be assessed by measuring the lactate levels as well as by finding out the ventilatory threshold, which is a non-invasive technique (Beaver et al., 2016; Wasserman, 1984). In addition to the carbon dioxide produced by aerobic metabolism after a certain level of exercise, an increase is observed in carbon dioxide production as a result of buffering of hydrogen ions (H^+) dissociated from accumulated lactic acid with bicarbonate. Ventilation begins to accelerate in reply to the nonmetabolic carbon dioxide released by buffering the H^+ (Wasserman, 1984). The point at which the linearity between minute ventilation (VE) and both carbon dioxide production (VCO_2) and oxygen intake (VO_2) is disrupted is called as the ventilatory threshold. If H^+ overlaps the buffering capacity of circulating bicarbonate, it causes the pH level of blood to deviate toward the acidic side, and resulting acidosis stimulates the carotid bodies, leading to hyperventilation (Wasserman, 1984). In addition, the slope of the curve indicating the correlation between VE and VCO_2 becomes steeper with hyperventilation. This additional ventilatory response is called as the Respiratory Compensation Point (Meyer et al., 2004).

As a result of anaerobic training stimuli, H^+ buffering capacity is expected to improve and due to relevant improvement, the ventilatory threshold levels are expected to boost. However, the study accomplished revealed no significant change in the values of ventilatory threshold VO_2 utilized to invasively determine the anaerobic threshold levels both before and after the high-intensity interval training applied ($p > .05$).

A significant increase was observed, however, in terms of respiratory compensation point VO_2 values of the experimental group after the training program, compared to the pre-training program ($p < .05$). The respiratory compensation point is characterized as the highest exercise point at which the metabolic acidity that proliferates as a result of the anaerobic metabolism starting to become active can be suppressed by the buffering systems of body (Erylmaz et al., 2018). The values in the respiratory compensation point zone represent the highest parameters at which the metabolic, cardiac, and respiratory systems of body demonstrate optimal endurance. The values obtained in this zone are, therefore, the criteria which can maintain significant advantages in analysing the conditions of athletes, sedentary individuals, and individuals with low fitness levels (Keir et al., 2024). At exercise intensities above the respiratory compensation point, metabolic acidosis becomes dominant, causing an athlete to terminate the exercise (Wasserman et al., 2015). Therefore, reaching the respiratory compensation point later means that individuals can continue exercising for longer periods of time and so have higher endurance capacities.

Some researchers have been claiming that the high-intensity trainings that covers anaerobic metabolism can improve the buffering capacity, deflecting the respiratory compensation point toward higher intensities (Chicharro et al., 2000). Accumulation of lactate and H^+ in large quantities during the high-intensity exercises can be a remarkable stimulus for adaptations of the systems responsible for regulating muscle pH (Bishop et al., 2011). Indeed, it has been pointed that the high-intensity interval trainings results with increases in the buffering capacity of muscles (Edge et al., 2006). It has also been indicated that the sprint training increases the buffering capacity of muscles, whereas such an improvement cannot be achieved via the aerobic endurance training (Sharp et al., 1986). The findings collected during our research suggest that the high-intensity interval training applied improves the buffering capacity, leading to an increase in the respiratory compensation point without any change in the ventilatory threshold and consequently prolongs the respiratory compensation point phase.

Another possible explanation for the longer respiratory compensation point phase as a result of the high-intensity interval training may be the percentage of fast-twitch muscle fibres. It has been claimed that the fast-twitch muscle fibres may have a higher buffering capacity, compared to the slow-twitch muscle fibres (Nakagawa et al., 2002).

CONCLUSION

Consequently, the high-intensity interval training applied in this study for a time period of eight weeks resulted with a significant increase in maximum power and average power values, which have remarkable effects on anaerobic performance ($p < .05$). Furthermore, significant increases were observed also in the values of $\text{VO}_{2\text{max}}$ (ml.kg.min^{-1}) and respiratory compensation point, which are crucial indicators of aerobic performance ($p < .05$). The results collected indicate that the practices of high-intensity interval training increase also the aerobic performance, particularly the anaerobic performance.

It can particularly beneficial, due to the favourable effects of high-intensity interval training on athletic performance, for athletes lacking adequate training time and for those who wish to reduce the duration and scope of training practices without experiencing any loss in $\text{VO}_{2\text{max}}$ and performance level throughout the pre-competition period. The practices of high-intensity interval training can, meanwhile, be applied also to the exercise routines of sedentary individuals, taking into account the loading principles, due to the favourable effects on cardiovascular health resulting from the surges in $\text{VO}_{2\text{max}}$.

AUTHOR CONTRIBUTIONS

The authors noted that there was equal participation in the elaboration of this document.

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No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

This study was produced from master thesis of Ardacan Yamen titled "*The effect of high intensity interval training on aerobic and anaerobic capacity*".

ETHICAL APPROVAL

Ethical approval was obtained from the Sivas Cumhuriyet University Non-Interventional Clinical Research Ethics Committee on December 14, 2022, under decision number 2022-12/26. The experiments were conducted in compliance with the applicable laws and regulations of the country in which they were performed. The authors affirm that the manuscript is honest, accurate, and transparent; that no significant aspects of the study have been omitted; and that any deviations from the original study plan have been clearly disclosed. This study adheres to all principles of ethical writing and publication.

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Physical demands of a national U20 rugby team in international tournaments

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ABSTRACT

The quantification of the load in rugby is an activity that has been carried out for some years. However, after reviewing the literature, there is little information on the demands that players present in international tournaments. The objectives of this research were to characterize the demands of players in international tournaments, to find out if there were significant differences depending on the specific position (forwards or backs), the parts of the game (first or second half) or the type of tournament (European vs. World Cup). To do this, a national team was quantified during all the matches they played in a European tournament and in a world tournament. All the players analysed were from the Under 20 category ($n = 32$). Each player wore a Catapult Vector S7 inertial device. Different ANOVA analyses were performed. The results showed differences in most of the variables analysed depending on the playing position, the part of the game and the type of tournament. In addition, the results showed a greater demand in players with a Back position who participated in the European tournament. In the process of individualization, training programs should be tailored according to players' positions on the field and their specific demands.

Keywords: Performance analysis, Team sport, Load monitoring, External load, Inertial devices, Ball in play.

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INTRODUCTION

Rugby is a sport that in recent years has experienced an increase in practitioners and followers, reaching 10 million practitioners around the world. (World Rugby, 2018). This increase is due to the increase in the number of people practicing team sports and seeking an intense activity with great physical demands (Cummins et al., 2013). For this reason, this modality, rugby, is characterized by being a contact sport, intermittent and with high intensity actions. These demands require the athlete to perform repeated running actions, collisions and static efforts of different jobs interspersed with rest periods (Duthie et al., 2003). This sport has evolved in recent years in the physical aspect of the players. Currently, rugby players perform a greater number of explosive actions, at greater intensity and for a longer duration than a few years ago. This fact has caused the practice of rugby to increase its visibility and number of practitioners due to its greater spectacle for fans.

As a result of these specifications in the load supported by the users of this sport, the incidence of injuries is one of the highest in team sports (Williams, et al., 2013) according to the different injury monitoring in recent years (Williams, et al., 2013; Cruz-Ferreira, et al., 2017). Williams et al. (2013) indicated that the incidence of injuries in senior men's professional rugby matches was 81 per 1000 player match hours. Rugby Europe's latest Injury Surveillance report, in the Under-20 category (U20), found an incidence rate of 83.33 injuries per 1,000 player match hours. Of the total injuries, 32.62% are serious and forced the athlete not to practice for at least 28.50 days (Cruz-Ferreira, et al., 2023c).

A typical match consists of two 40 min halves separated by 10–15 min, with frequent intense bouts of high-intensity activities such as running, kicking, passing, and tackling interspersed with low-intensity exercise (Gabbett et al., 2008). Furthermore, during a match rugby players perform a high number of accelerations and decelerations with change of direction involving eccentric muscle actions (Gabbett et al., 2008). Because of these demands, significant skeletal muscle fatigue and muscular damage are reported after a rugby match (Tavares et al., 2017). Inappropriate management of training load (TL) has quickly become one of the main risk factors in non-contact injuries (Soligard et al., 2016; Jones et al., 2017) or increased levels of fatigue, as well as higher risk of illness (Jones et al., 2017).

To facilitate this handicap and provide knowledge, in recent years, the use and exploitation of microtechnology in sports has been exponential. Although rugby was the first sport in which technology was used to quantify player demands, football popularized this technique and helped improve the process. Rugby has used Global Positioning Systems (GPS) using IMUs with microsensor technology (Jones et al., 2015) since 2008 to quantify volume and intensity during competition (Hartwig et al., 2008) and training load (Cunniffe et al., 2011) since 2011. Currently, it has been studied at senior club level (Takamori et al., 2022) and at international level (Olsen et al., 2023). But current information on the U20 category is limited.

Reviewing the existing literature, we are unaware of the existence of studies that analyse the U20 category at different competitive levels at an international level. Therefore, the objective of our study were: i) To describe the demands that rugby presents in a world championship and in a European championship in the U20 category; ii) To analyse whether there are differences between both championships carried out by the same team; iii) To find out whether there are differences in the load demands of the players depending on the playing position.

MATERIALS AND METHODS

Design

The design of the present study is framed within an empirical methodology, specifically a quasi-experimental study (Ato, López, & Benavente, 2013), whose objective is to understand the external load demands of rugby players during an international championship. The quasi-experimental design is because the objective of the research is to test a hypothesis by manipulating a variable since a random group design cannot be carried out.

Participants

The research consisted of 32 international level U20 rugby players. The analysed team comprised 15 Back position players (average weight of 83.6 ± 7.5 kilograms and an average height of 178.9 ± 5.3 cm) and 17 Forwards position players (average weight of 104 ± 7.0 kilograms and an average height of 187.7 ± 7.4 cm).

Sample

The sample of this research consisted of 11 matches (5 matches from the European Championship and 6 matches from the World Rugby U20 Trophy Championship) involving a total of 417 cases ($n = 417$). Each player was equipped with a Catapult inertial device, which was attached to the athlete using a sport-specific anatomical harness. The research was conducted under the criteria of the bioethics committee issued to the university to which the researchers belong.

Instruments

All players were equipped with a GPS device Catapult Vector S7 (Catapult, Melbourne, Australia) with a recording capacity of 10Hz, which was attached using a fitted anatomical harness suitable for sports practice.

Variables

The research included the variables playing position (backs and forwards), match period (first half and second half), and tournament (World or European), which were selected by the research team as independent variables. Additionally, the following were used as dependent variables:

- Play time: This is the number of minutes that the game has been in play (measured in minutes).
- Total distance: Number of meters covered by the players during the game (measured in meters).
- Distance at $>7\text{km/h}$: Number of meters covered by the players during a game at a speed greater than 7 km/h. (measured in meters).
- High intensity distance: Number of meters covered by the players during the game at a speed greater than 16 km/h (measured in meters).
- Distance/Minute: Number of meters covered per minute of play (measured in meters).
- Accelerations and decelerations: Number of times that the athlete makes a positive or negative increase of 2 m/s^2 in the speed of movement.
- Accelerations/min: Number of times that the athlete makes a positive increase in the speed of movement per minute of play
- Player load: calculates the physical effort of the athlete during the movement. It calculates it by adding the acceleration in all directions, based on each of the 3 axes and the time of the acceleration.
- RHIE total bouts: Repeated high intensity efforts provide the ability to identify periods where athletes have performed repeated "*high intensity*" speed efforts without adequate recovery. Successive single high intensity efforts repeated within a predetermined time frame are grouped into RHIE bouts.

- **Contact involvement count:** Calculates the cumulative sum of player load from 0 to 20 seconds after contact involvement. If greater than 1.0, the player is considered active after contact involvement. Otherwise, the player is considered passive.

The analysis of the variables was conducted only during the moments when the ball was in play (Ball in Play, BIP). Therefore, all moments when the match did not meet this BIP condition were excluded.

Procedure

First of all, A meeting was held with the staff of the selected national team. General information about the research was provided, as well as any doubts and questions they had were answered. Once the request was accepted by the national team, a meeting was held between the coaching staff and the players where the research that was going to be carried out was explained, the positive aspects of the results obtained and that it did not pose any risk to the players.

Prior to the championships, the players began to train with the material that was going to be used in the matches so that ignorance or discomfort could be a contaminating variable in the research. Next, all players were equipped before each match 45 minutes prior to the start of the match. Only the players who were playing in the match were taken into account for the analysis (the players who were on the bench were not analysed). Furthermore, with the information from the players and the analysis of the match, the Ball in Play (BIP) moments were selected and the results obtained were analysed.

Statistical analysis

Assumption checks were performed to ensure that the recorded variables met the normality criteria (Kolmogorov-Smirnov test). Therefore, a non-parametric hypothesis testing model was used. A descriptive analysis (means and standard deviation) was carried out to explain the behaviour of the dependent variables during the performance in the competition. Additionally, independent samples T-tests were conducted to compare based on the different independent variables (Field, 2009). The significance level used was $p < .05$, and the software used was SPSS 25.0 (Field, 2009)

RESULTS

Table 1 shows the results of the load values obtained by the study participants based on the type of tournament (World or European) and the part of the match (first half and second half). The results indicate significant differences related to the load borne by the players depending on the type of tournament and the part of the match. The results show that the first halves of matches in both World and European tournaments are more intense and place greater demands on the athletes than the second halves.

On the other hand, Table 2 provides information related to the players' positions on the field (distinguishing between backs and forwards). As can be seen, players in the Back position perform higher intensity actions and greater effort in physical variables compared to players in the Forwards position in both World and European championships.

DISCUSSION

Load quantification in rugby competitions is a common practice when dealing with high-level competitive teams. This research aimed to understand the differences in demands borne by players of a national team in different international U20 tournaments.

Table 1. Descriptive and inferential results of the matches grouped by tournament and match period.

	European Tournament					World Rugby Trophy					ANOVA
	First half		Second half		Sig.	First half		Second half		Sig.	
	Mean	ST	Mean	ST		Mean	ST	Mean	ST		
Play time	34.95	7.71	27.46	13.09	.001*	30.02	14.70	21.42	15.66	<.000*	.001*
Total distance	3660.15	745.48	2860.49	1355.77	<.000*	2432.47	732.06	1656.34	938.35	<.000*	<.000*
Distance at <7 km/h	2386.38	524.71	1863.50	892.66	.001*	1343.12	279.88	888.66	438.93	<.000*	<.000*
High intensity distance	758.57	365.89	583.07	383.91	.017*	989.89	542.02	602.83	474.90	<.000*	.073
Accelerations & decelerations	53.00	31.20	41.41	31.72	.059	26.93	13.84	17.88	13.38	<.000*	<.000*
Player load	405.18	87.74	320.42	148.83	.001*	256.57	58.69	174.66	86.76	<.000*	<.000*
RHIE total bouts	18.10	7.26	14.13	8.51	.012*	8.41	4.26	5.15	4.04	<.000*	<.000*
Contact involvement count	18.89	11.05	14.92	11.28	.068	11.95	6.38	6.89	5.78	<.000*	<.000*
Metres per minute	105.97	17.87	103.58	16.74	.472	91.99	24.79	89.25	24.92	.349	<.000*
High speed running	20.29	8.34	20.26	7.67	.983	17.85	10.14	15.82	9.34	.076	<.000*
Acc/min	0.68	0.40	0.70	0.52	.408	0.56	0.44	0.50	0.41	.246	.089

Play Time: This is the number of minutes that the game has been in play (measured in minutes); **Total Distance:** Number of meters covered by the players during the game (measured in meters); **Distance at >7km/h:** Number of meters covered by the players during a game at a speed greater than 7 km/h. (measured in meters); **High Intensity Distance:** Number of meters covered by the players during the game at a speed greater than 16 km/h (measured in meters); **Distance/Minute:** Number of meters covered per minute of play (measured in meters); **Accelerations and Decelerations:** Number of times that the athlete makes a positive or negative increase of 2 m/s² in the speed of movement; **Accelerations/min:** Number of times that the athlete makes a positive increase in the speed of movement per minute of play; **Player Load:** calculates the physical effort of the athlete during the movement. It calculates it by adding the acceleration in all directions, based on each of the 3 axes and the time of the acceleration; **RHIE total bouts:** Repeated high intensity efforts provide the ability to identify periods where athletes have performed repeated "high intensity" speed efforts without adequate recovery. Successive single high intensity efforts repeated within a predetermined time frame are grouped into RHIE bouts; **Contact Involvement Count:** Calculates the cumulative sum of player load from 0 to 20 seconds after contact involvement. If greater than 1.0, the player is considered active after contact involvement. Otherwise, the player is considered passive.

Table 2. Descriptive and inferential results grouped by playing position according to the type of competition.

	European Tournament					World Rugby Trophy					ANOVA
	Back		Forwards		Sig.	Back		Forwards		Sig.	
	Mean	ST	Mean	ST		Mean	ST	Mean	ST		
Play time	32.42	11.60	29.09	11.73	.138	25.94	15.63	23.91	15.98	.269	.115
Total distance	3537.61	1127.35	2918.64	1203.71	.007*	2165.13	927.57	1798.84	923.47	<.000*	<.000*
Distance at <7 km/h	2352.91	739.57	1864.66	788.99	.001*	1215.90	416.89	948.36	429.02	<.000*	<.000*
High intensity distance	941.85	348.71	429.73	231.59	<.000*	1183.54	486.76	409.20	245.47	<.000*	<.000*
Accelerations & decelerations	57.38	32.37	37.38	28.80	.001*	31.78	13.62	13.09	7.82	<.000*	<.000*
Player load	349.57	113.98	360.27	147.70	.677	210.07	76.90	204.50	93.95	<.578	.965
RHIE total bouts	19.24	7.89	13.04	7.45	<.000*	9.22	4.33	4.19	2.99	<.000*	<.000*
Contact involvement count	12.69	8.65	19.62	12.25	.001*	7.35	4.43	10.13	7.58	<.000*	<.000*
Metres per minute	110.94	14.71	99.53	17.42	<.000*	96.08	26.33	85.67	22.64	<.000*	<.000*
High speed running	26.63	5.98	15.25	5.19	<.000*	23.60	7.85	10.94	6.97	<.000*	<.000*
Acc/min	2.34	0.60	0.54	0.39	.250	0.756	0.44	0.34	0.29	<.000*	.197

Play Time: This is the number of minutes that the game has been in play (measured in minutes); **Total Distance:** Number of meters covered by the players during the game (measured in meters); **Distance at >7km/h:** Number of meters covered by the players during a game at a speed greater than 7 km/h. (measured in meters); **High Intensity Distance:** Number of meters covered by the players during the game at a speed greater than 16 km/h (measured in meters); **Distance/Minute:** Number of meters covered per minute of play (measured in meters); **Accelerations and Decelerations:** Number of times that the athlete makes a positive or negative increase of 2 m/s² in the speed of movement; **Accelerations/min:** Number of times that the athlete makes a positive increase in the speed of movement per minute of play; **Player Load:** calculates the physical effort of the athlete during the movement. It calculates it by adding the acceleration in all directions, based on each of the 3 axes and the time of the acceleration; **RHIE total bouts:** Repeated high intensity efforts provide the ability to identify periods where athletes have performed repeated "high intensity" speed efforts without adequate recovery. Successive single high intensity efforts repeated within a predetermined time frame are grouped into RHIE bouts; **Contact Involvement Count:** Calculates the cumulative sum of player load from 0 to 20 seconds after contact involvement. If greater than 1.0, the player is considered active after contact involvement. Otherwise, the player is considered passive.

A review of the literature shows there is not much information available for this sports stage. Therefore, with the results obtained, the intention is to determine if the analysed U20 players show similar results to professional athletes in the senior category.

Results based on match period

The results grouped based on the match period show that the first halves of all matches (both in European and World competitions) are more intense and require athletes to make a greater number of efforts. These efforts lead to a higher accumulated load than in the second halves of the matches. Firstly, the average time of the analysed matches shows greater utilization in the European tournament matches, making the game more continuous. Additionally, the first halves in both the European and World tournaments have more playtime than the second halves. In line with this, Guerrero-Esteban et al., (2023) demonstrated that playtime in rugby can be affected by different variables, making it difficult to generalize a value. Regarding the total distance covered, the results show distances close to 3000 meters per half during the European tournament, while the results during the World matches drop to an average of 2000 meters per half. These results align with some data observed in the literature (Blair et al., 2017; Clarke et al., 2016), where the distance covered in both studies is lower than the results obtained here. In contrast, Suarez-Arrones et al. (2016) in their research on women's rugby showed results closer to those obtained in this research.

In line with the distance covered, it is interesting to analyse the distance covered at speeds of 7 km/hour. The results for this variable show a significant difference between championships (European tournament matches show higher values than World Cup matches). Additionally, in terms of match periods, the first halves show higher results than the second halves. These results contradict existing literature. On one hand, van den Berg et al. (2017) demonstrated that the results between the two halves were usually similar. Similarly, Portillo et al. (2014) also showed that the results between match periods were usually similar. Furthermore, related to distance, in the high-intensity distance variable, this research's results show that the first halves are more intense and require players to cover more distance at this intensity than in the second halves. However, during the World Cup matches, the results are higher than during the European matches. Finally, the meters per minute variable provides information on the distance players cover per minute, indicating the match's intensity. The matches played in the European tournament show higher values than those played in the World Cup. Additionally, the first halves are more intense than the second halves. Goodale et al. (2017) in their research showed similar data where the first halves of matches were more intense than the second halves. However, Ross et al (2015) found a higher intensity in the analysed matches compared to the results obtained in this research. Conversely, Ganatalli et al. (2014) provided lower data than those obtained in this research. The main reasons for such dispersion and variety in the results could be the competitive level of the analysed samples.

The results obtained for the acceleration and deceleration variables show significant differences between tournaments. In line with the results obtained, different investigations demonstrated in players values similar to those obtained in this investigation (Varley et al., 2012). In addition, in a sample of under-20 players Cunningham et al. (2016) demonstrated these differences mentioned. These similarities may be due to the fact that there are many similarities between the samples analysed and the sample of this investigation.

Results based on playing position

Results analysed based on playing position demonstrate that Back players in both the European tournament and World Cups show higher game demands than Forward players.

The distance covered by players also varies based on their playing position on the field. Back players covered greater distances in both the European tournament and World Cups compared to Forward players. These results are consistent with those found in Portillo et al.'s research (2014). In contrast to this assertion, Ross et al. (2014) demonstrated that in rugby sevens, another form of rugby with similar principles to the analysed rugby, Forward players cover greater distances than Back players. The distance covered per minute by players is also higher among Back players than Forward players in both tournaments. The values obtained exceed those shown by Cunningham et al. (2016) in both U20 and amateur samples across different tournament phases. Conversely, Suárez-Arrones et al. (2016) found higher results in a sample of rugby sevens compared to those obtained in this research. The main differences in distance per minute can be found in the competitive level of the analysed sample. However, in rugby sevens, despite it being the same playing field, with fewer participants, the intensity and player involvement are higher, leading to greater intensity in the game.

The results show that Back players performed a greater number of accelerations and decelerations compared to Forward players. Consistent with these findings, Ball et al. (2019) demonstrated that in various rugby situations, Back players not only performed more accelerations and decelerations but also at higher intensity. In another analysed sample, Goodale et al. (2017) obtained similar results in women. The main reasons possibly related to these differences could be the inherent game demands and the different actions required of each player based on their position.

The High Intensity Events (HIE) conducted indicate a higher number of actions in Back players, with more occurring during the European tournament than the World Cup. Sheehan et al. (2022) showed that HIE values are related to the competitive level and the player's position on the field. These values are difficult to generalize and are multifactorial. In line with the above, Negro and Gabbett (2015) obtained lower HIE values in both professional and semi-professional players.

Conclusions and practical applications

Analysing the results obtained in this research, it can be concluded that the demands on an international U20 team vary depending on the type of tournament they participate in. The results show significant differences between the demands of the European tournament and those of the World Cup. Additionally, the matches analysed in both tournaments were characterized by being more intense in the first halves compared to the second halves, with the analysis between halves of the match being significant. Lastly, Back players achieved higher values in variables related to accelerations, decelerations, and all distance-related variables (including high-intensity ones), leading to significant differences between positions (Backs and Forwards).

The main practical applications of this research are related to player training processes. The data obtained provide information for individualizing training processes. These results can help coaches and physical trainers understand the demands athletes face during competition. Furthermore, in the process of individualization, training programs should be tailored according to players' positions on the field and their specific demands. Lastly, regarding match planning, observing that first halves are more intense than second halves can assist coaches in making decisions regarding player selection throughout the game.

AUTHOR CONTRIBUTIONS

DMT and MRR contributed to the conceptualization and design of the study. Data collection was carried out by MRR and HAF, while MAP was responsible for data curation and organization. The formal data analysis was conducted by DMT, HAF, and MAP. DMT contributed to the interpretation of the findings. The original

draft of the manuscript was prepared by MRR, HAF, and DMT. All authors participated in reviewing and editing the manuscript critically, approved the final version, and take responsibility for the integrity of the work.

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No potential conflict of interest was reported by the authors.

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Comparison of anthropometric and performance characteristics in elite male football and handball players

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ABSTRACT

Elite-level athletes develop distinct performance profiles shaped by training regimens tailored to the specific physical and physiological demands of their respective sports. The nature of the sport, training methods, and game dynamics directly influence the development of strength, power, speed, and anthropometric characteristics. In team sports, comparative evaluations of these attributes are critical for accurate performance analysis and the design of sport-specific and individualized training pro-grams. This study aimed to compare the anthropometric characteristics, strength, ex-plosive power, and speed parameters of elite male football and handball players. A total of 44 athletes (22 football players and 22 handball players) participated in this cross-sectional comparative study. Anthropometric data included height (cm), body weight (kg), and body mass index (BMI, kg/m²). Performance assessments comprised leg strength (kg), handgrip strength (kg), vertical jump height (cm), 30-meter sprint time (s), and peak power output (W). Independent samples t-tests revealed statistically significant differences between football and handball players in age ($p = .004$), height ($p = .005$), leg strength ($p = .007$), and handgrip strength ($p < .001$). No significant differences were found in other performance variables ($p > .05$). The findings indicate that elite football and handball players exhibit sport-specific anthropometric and performance profiles. Football players showed greater lower-body strength, while hand-ball players had superior upper-body strength and greater stature. These differences underscore the importance of developing training protocols and talent identification strategies that reflect the unique demands of each sport. Coaches are encouraged to utilize sport-relevant performance tests and interpret results contextually to optimize athlete development and specialization.

Keywords: Performance analysis, Sport-specific training, Motor abilities, Anthropometric characteristics, Physiological profiling.

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INTRODUCTION

Elite athletes undergo intensive and systematic training processes tailored to the specific physical, physiological, and neuromuscular demands of their respective sports, shaping their performance in accordance with the requirements of their discipline (Akçınar & Macit, 2020; Viru, 2017; Brewer, 2017). The nature of the sport, its structural and temporal dynamics, and training modalities directly influence the development of key motor characteristics such as strength, power, speed, and agility (Reza et al., 2024; Formenti et al., 2021; Young, Dawson & Henry, 2015; Strafford et al., 2018). Consequently, athletes participating in different sports disciplines develop distinct performance profiles in response to sport-specific training stimuli (Reza et al., 2024). Scientifically identifying these performance differences allows for a better understanding of athletes' needs and facilitates the design of individualized training programs.

In team sports, performance is not solely determined by technical and tactical skills but is also closely linked to physical capacity (Forsman, et al., 2016; Montenegro Bonilla et al., 2024; Eusebio, Prieto-González, & Marcelino, 2025). Parameters such as strength (Ioannis, 2013), explosive power (Aksović et al. 2020), and speed (Singh et al., 2024; Ben Brahim et al., 2021) are among the fundamental factors that influence athletic effectiveness during competition. The development of these parameters is critical both for general motor performance (İlbak & Akarsu, 2022) and for the effective execution of sport-specific skills (Montenegro Bonilla et al., 2024; Bishop & Girard, 2013). In this context, comparative evaluations of the physical performance characteristics of athletes across different sports disciplines significantly contribute to both coaching decision-making and the scientific knowledge base surrounding athlete development.

Football and handball are two distinct team sports that differ markedly in terms of playing field dimensions, level of physical contact, movement patterns, and energy system demands. Football is played on a large field and relies heavily on aerobic capacity, repeated sprint ability, change of direction skills, and lower limb strength (Curtis et al., 2019; Strudwick, 2016; Nobari et al., 2023). In contrast, handball is a high-intensity sport played in a smaller area, characterized by frequent physical collisions, rapid offensive-defensive transitions, and an emphasis on upper-body strength and explosive jumping ability (Srce & Računski Centar, 2025; Machado et al., 2013). These differences likely result in divergent training content and physiological adaptations for athletes in each sport, fostering sport-specific development patterns in performance-determining attributes such as strength, power, and speed.

Existing literature reports that football players typically demonstrate superior values in aerobic endurance (Manouvrier, Cassirame, & Ahmaidi, 2016), repeated sprint ability (Nowak et al., 2025), and lower-extremity motor skills (Komarudin et al., 2022; Castagna et al., 2006), whereas handball players exhibit advantages in upper-body strength (Rahman & Sharma, 2023; Hermassi et al., 2016), explosive jumping ability, and anaerobic power output (Wagner, Fuchs, & von Duvillard, 2018; Kyriacou-Rossi, Hadjicharalambous, & Zaras, 2024; Muhammad & Allawy, 2023). However, studies directly comparing these two sports using standardized methodologies and multidimensional neuromuscular performance metrics remain limited. Interdisciplinary comparative research—particularly in areas such as strength modalities, sprint performance, and explosive power—plays a crucial role in advancing performance science and in clarifying the sport-specific physical requirements of different athletic disciplines.

In this context, the aim of the present study is to comparatively examine the anthropometric characteristics, strength, explosive power, and speed parameters of elite football and handball players. The findings obtained are expected to provide valuable insights for identifying sport-specific performance profiles, optimizing

training programs accordingly, and grounding talent identification and selection processes in more scientific principles.

MATERIALS AND METHODS

Participants

The minimum required sample size for this study was determined through an a priori power analysis conducted using G*Power version 3.1.9.7. The analysis was based on an effect size of 0.80, a significance level (α) of .05, and a statistical power ($1-\beta$) of 0.80. The results indicated that a total of at least 42 participants—21 per group—would be sufficient. Accordingly, the study included a total of 44 male athletes: 22 active football players and 22 active handball players. All participants had been training regularly and competing actively in their respective sports for a minimum of three years.

Specific inclusion criteria were applied to determine eligibility for participation. These criteria included: being male, aged between 18 and 30 years, having a minimum of three years of regular training experience in football or handball, being free from any chronic illness or musculoskeletal disorder, and signing an informed consent form. Exclusion criteria included: falling outside the specified age range, having experienced a serious injury within the past six months, lacking consistent training history, being unfit for testing on the test day due to health reasons, and failure to provide informed consent. Descriptive statistics for both groups are presented in Table 1.

Table 1. Descriptive statistics of the groups

Variable	Group	Minimum	Maximum	Mean	Standard Deviation
Age (years)	Football	19	26	22.64	1.76
	Handball	17	26	20.18	3.30
Training experience (years)	Football	5	20	10.59	3.74
	Handball	5	16	9.00	2.43
Height (cm)	Football	165	191	177.09	6.05
	Handball	176	197	182.50	6.14
Body weight (kg)	Football	67.50	87.30	75.67	6.05
	Handball	65.90	102.00	79.89	9.10
BMI (kg/m ²)	Football	21.19	26.92	24.14	1.66
	Handball	20.80	28.86	23.96	2.23

Research design

This study was conducted using a comparative cross-sectional research design. The sample included a total of 44 male athletes, comprising 22 football players and 22 handball players. The data collection process commenced after obtaining ethical approval from the Düzce University Ethics Committee (approval number: 2025/74; date: 27.02.2025). During the first session, the purpose, scope, and procedures of the study were explained to the participants both verbally and in written form, in a clear and comprehensible manner. Written informed consent was obtained from all participants, and the study was conducted in accordance with ethical principles. In the second session, anthropometric measurements were collected. These included height (cm), body weight (kg), and body mass index (BMI, kg/m²), along with demographic information such as chronological age and training age. Additionally, pilot testing protocols were implemented to familiarize participants with the testing procedures and to minimize potential measurement errors during the actual data collection. In the third session, the participants underwent the main performance tests, which included

measurements of leg strength (kg), handgrip strength (kg), vertical jump height (cm), sprint time (seconds), and peak power output (Watts). The data obtained from these tests were statistically analysed and the results were interpreted and reported accordingly. An overview of the research design and procedural flow is presented in Figure 1.

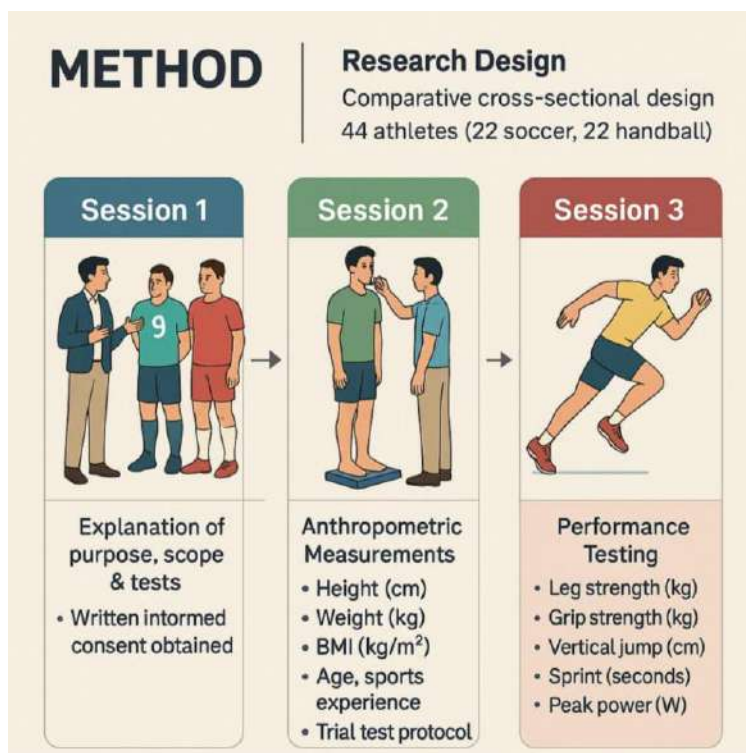


Figure 1. An overview of the research method.

Anthropometric measurements

All anthropometric measurements in this study were conducted by a trained researcher in accordance with the standards of the International Society for the Advancement of Kinanthropometry (ISAK) (Olds & Stewart, 2006). Standardized measurement tools were used throughout the data collection process. All data were gathered with strict adherence to reliability and validity principles, including repeated measurements and regular device calibration.

Height measurement

Participants' height was measured while they stood barefoot in an upright position, with their head aligned to the Frankfurt horizontal plane. Measurements were taken using a Seca 213 portable stadiometer (Seca GmbH & Co. KG, Hamburg, Germany), and values were recorded in centimetres (cm). During measurement, participants' heels, buttocks, back, and head were in contact with the vertical measurement plane to ensure accuracy.

Body weight measurement

Body weight was assessed while participants stood on a flat and stable surface, barefoot and wearing light clothing, in an upright posture. Measurements were obtained using an Omron HN-289 digital scale (Omron Healthcare Co., Ltd., Kyoto, Japan) and recorded in kilograms (kg). Prior to each use, the device was checked to ensure proper functioning.

Body Mass Index (BMI)

BMI was calculated using participants' height and body weight data. The Body Mass Index was computed by dividing body weight in kilograms by the square of height in meters, using the following formula:

$$\text{BMI (kg/m}^2\text{)} = \text{Body Weight (kg)} / \text{Height (m)}^2$$

Performance tests

The physical performance tests implemented in this study aimed to assess the participants' fundamental motor characteristics, such as strength, power, and speed. To obtain valid and reliable results, tests were administered in a specific sequence, taking into consideration participants' energy systems and muscle fatigue levels (Brown & Weir, 2001; Mackenzie, 2005). Prior to the testing protocol, participants completed a dynamic warm-up routine recommended by Kurak et al. (2024). The testing sequence began with the 30-Meter Sprint Test, which assesses high-intensity anaerobic capacity. Administering this test early ensures that the central nervous system and major muscle groups are not yet fatigued, preserving sprint performance accuracy. Next, the Vertical Jump Test was conducted to evaluate lower-body explosive strength. At this point, lower-limb muscles remained active, minimizing external impact on jump performance. Jump height data obtained from this test were then used to calculate peak power output using the Harman formula (Harman et al., 1991), thus evaluating not only jump height but also the power produced. Following the jump test, lower-body strength was measured using a Takei brand leg dynamometer. Since this isometric test induces less metabolic fatigue than dynamic efforts, its placement at this stage was deemed appropriate. Lastly, the Handgrip Strength Test was administered to assess upper-body strength. Due to its low energy demand and minimal interference from previous tests, it was placed at the end of the sequence. Adequate recovery periods (3–4 minutes) were provided between tests to minimize any residual effects and ensure accurate performance representation.

30-meter sprint test

The 30-Meter Sprint Test was used to assess participants' short-distance sprinting performance. The test was conducted on a flat, non-slip surface marked with a 30-meter sprint track. Participants wore appropriate sports attire and received standardized warm-up and test instructions beforehand. The sprint started from a stationary standing position, and reaction time was not included in the measurement. Sprint times were recorded using photocell timing gates (Brower Timing Systems, Utah, USA) placed at the start and finish lines. Each participant was given two trials with a 4-minute rest between attempts. The best sprint time, measured in seconds, was used for analysis (Mackenzie, 2005).

Vertical jump height

To evaluate lower-limb explosive power, a squat jump test was administered (Mackenzie, 2005; Loturco et al., 2020). Participants began in an upright position, descended to approximately 90° of knee flexion, held this position for three seconds, and then performed a maximal vertical jump with hands placed on the hips. Arm swing was restricted to isolate the contribution of the lower-extremity muscles. Jump height was measured using the Optojump Next vertical jump analysis system (Microgate, Bolzano, Italy), which uses infrared optical sensors. Data were collected via a module fixed to the participant's waist and synchronized with the system. Results were recorded in centimetres (cm). Each participant completed two trials, with 4-minute rest intervals. The best result was used for analysis (Glatthorn et al., 2011).

Peak power calculation

Using jump height values, peak power output of the lower limbs was calculated with the Harman equation (Harman et al., 1991), which incorporates both body mass and jump height:

$$\text{Peak Power (W)} = 61.9 \times \text{Jump Height (cm)} + 36.0 \times \text{Body Mass (kg)} + 1822$$

This equation estimates explosive power potential in watts (W) based on vertical jump performance.

Lower body strength test

To assess isometric lower-body strength, a standard protocol using a Takei leg dynamometer (Takei Scientific Instruments Co., Ltd., Japan) was applied (Harman et al., 1991). This test targets major muscle groups around the knee joint, particularly the quadriceps and hamstrings. Participants stood on a stable surface with feet shoulder-width apart. The grip bar connected to the dynamometer was adjusted according to the individual's height and leg length, ensuring approximately 130–140° of knee flexion, an optimal angle for maximal isometric force production. Participants were instructed to maintain an upright posture and pull the bar upward with maximum force using only the lower body, while keeping hands in a static grip and avoiding involvement of the upper body. Posture was strictly monitored to eliminate upper-body contribution. Two trials were allowed per participant, with a 60-second rest between trials. The highest value, measured in kilograms (kg), was used in the analysis (Eyuboglu et al., 2019).

Grip strength test

To assess handgrip strength, a digital hand dynamometer (Takei T.K.K. 5401, Japan) was used. The test was performed using only the participant's dominant hand. During testing, participants stood upright in a neutral anatomical position, arms relaxed at their sides, and elbows fully extended. The dynamometer was adjusted to fit each participant's hand size for optimal grip comfort. Participants were instructed to squeeze the device as hard as possible for three seconds without moving their body (i.e., no swinging or pressing with the torso). Two trials were conducted with a 60-second rest between them. The highest value, recorded in kilograms (kg), was included in the analysis (Mackenzie, 2005).

Statistical analysis

All data obtained from the study were analysed using IBM SPSS Statistics for Windows, Version 26.0 (IBM Corp., Armonk, NY, USA). To examine the distribution characteristics of the data, skewness and kurtosis coefficients were initially assessed. Values for each variable falling within the range of -2 to +2 were interpreted as indicating a normal distribution (Kim, 2013; Mishra et al., 2019). Prior to between-group comparisons, Levene's Test for Equality of Variances was conducted to assess the homogeneity of variances across independent samples. The results of this test were taken into account to determine which version of the independent samples t-test would be applied for group comparisons. To evaluate statistical differences in means between the football and handball groups, the Independent Samples t-test was used. For all analyses, the level of statistical significance was set at $p < .05$.

RESULTS

The findings obtained based on the data collected in this study are presented in Table 2.

Table 2 shows that there were statistically significant differences between football and handball players in age ($p = .004$), height ($p = .005$), leg strength ($p = .007$), and grip strength ($p < .001$). Football players were older and had higher leg strength, while handball players were taller and had greater grip strength. No significant differences were found in sports age, weight, BMI, vertical jump, sprint time, or peak power ($p > .05$).

Table 2. Comparison of physical characteristics and performance indicators of football and handball players.

Variable	Group	Mean $\pm$ SD	t	df	p
Age (years)	Soccer	22.64 $\pm$ 1.76	3.075	32.034	.004*
	Handball	20.18 $\pm$ 3.30			
Sports age (years)	Soccer	10.59 $\pm$ 3.74	1.674	42	.102
	Handball	9.00 $\pm$ 2.43			
Height (cm)	Soccer	177.09 $\pm$ 6.05	-2.944	41.990	.005*
	Handball	182.50 $\pm$ 6.14			
Weight (kg)	Soccer	75.67 $\pm$ 6.05	-1.809	42	.078
	Handball	79.89 $\pm$ 9.10			
BMI (kg/m ²)	Soccer	24.14 $\pm$ 1.66	0.299	42	.766
	Handball	23.96 $\pm$ 2.23			
Leg strength (kg)	Soccer	214.07 $\pm$ 30.59	2.883	33.756	.007*
	Handball	176.68 $\pm$ 52.58			
Grip strength (kg)	Soccer	45.18 $\pm$ 4.76	-4.675	42	.000*
	Handball	52.40 $\pm$ 5.46			
Vertical jump (cm)	Soccer	34.27 $\pm$ 4.19	1.643	42	.108
	Handball	31.88 $\pm$ 5.38			
Sprint (s)	Soccer	4.39 $\pm$ 0.25	1.740	42	.089
	Handball	4.28 $\pm$ 0.16			
Peak Power (W)	Soccer	6667.62 $\pm$ 320.61	-0.030	34.733	.976
	Handball	6671.53 $\pm$ 525.46			

Note. * $p < .01$.

DISCUSSION

This study aimed to comparatively examine the anthropometric characteristics, strength, power, and speed parameters of elite-level football and handball players. The findings revealed statistically significant differences between the two groups, particularly in terms of upper and lower extremity strength and height. These results support the discipline-specific performance profiles reported in the existing literature.

With regard to anthropometric parameters, handball players were found to be significantly taller than football players, while the difference in body weight, although not statistically significant, indicated that handball players tend to be heavier. The absence of a significant difference in BMI suggests that both groups possess a similar body composition. This may reflect comparable training loads and conditioning levels across the two sports. The height difference may be associated with sport-specific requirements in handball, where longer upper limb reach offers a positional advantage and influences talent selection (Milanese et al., 2011; Mohamed et al., 2009). Conversely, football players are known to benefit from a more compact and agile physique, which enhances mobility on the field (Bajramovic et al., 2019; Mijalković, Mladenović, & Ilić, 2023). These observations underscore the influence of sport-specific demands in shaping body composition and anthropometric profiles, as well as the role of training regimens in maintaining these characteristics (Granados et al., 2007; Matthys et al., 2011).

Despite the finding that football players exhibited significantly higher lower extremity strength (leg strength) than handball players, the current literature does not consistently support this claim. For instance, Risberg et al. (2018) reported that elite female handball players demonstrated 11% greater quadriceps strength than

football players, a difference that remained significant (4.1%) even after normalization for body weight ($p < .001$ and $p = .012$). No significant difference was found in hamstring strength; however, the hamstring-to-quadriceps (H:Q) ratio was lower in handball players (0.58 vs. 0.60; $p < .02$). These findings suggest that although handball players may exhibit higher quadriceps strength, their hamstring strength may be disproportionately low. Nevertheless, numerous studies have emphasized the critical role of lower extremity strength in football performance (Gil et al., 2018; Coratella et al., 2019). The sport's large playing field, high-volume running, and lower-body-focused technical skills promote notable hypertrophy and strength development in the lower limbs (Curtis et al., 2019; Strudwick, 2016). These physiological adaptations may contribute to superior performance in leg strength tests among football players. However, the absence of consensus in the literature highlights the need for further empirical investigation.

The significantly higher handgrip strength observed in handball players can be attributed to the sport's intrinsic reliance on upper extremity function. Handball requires high-speed throwing, frequent physical contact, and advanced upper-body coordination, all of which stimulate the development of upper limb musculature (Srce & Računski Centar, 2025; Machado et al., 2013). Therefore, it is expected that handball players outperform football players in upper-extremity-specific strength measures such as grip strength. Previous studies have demonstrated a strong association between handgrip strength and throwing velocity in handball, indicating its critical role in performance (Saavedra et al., 2018). Additionally, upper-body strength assessments such as the medicine ball throw have been shown to be effective in talent identification among youth handball players (Tsoukos et al., 2019). These findings support the notion that handball players hold an advantage over football players in motor tasks requiring upper body strength.

No statistically significant differences were identified between the two groups in sprint time, vertical jump, or peak power output. This lack of difference may be attributed to the similar physical demands and training methodologies in both sports. High-intensity, intermittent activities requiring speed, agility, and explosive strength are fundamental to both football and handball, potentially leading to convergent physiological adaptations (Halder & Rahaman, 2022). Shared emphasis on sprinting and agility in training programs may also contribute to similar performance outcomes in these parameters. Some studies have further noted that even among elite and sub-elite football players, vertical jump performance does not always differ significantly, indicating that such metrics may lack discriminatory power across sport disciplines (Kalata et al., 2023). Additionally, the limited correlation between sprinting and jumping abilities (Boone et al., 2021) suggests that these capacities are distinct and should be evaluated independently. Although group-level similarities were found, individual differences – including biomechanical structure, flexibility, and specific training focuses – may still play a decisive role in performance, which cannot be fully captured by group comparisons. This underscores the importance of evaluating athletic performance not only through group averages but also by considering individual variability.

Nevertheless, some methodological limitations should be taken into account when interpreting the findings. The relatively small sample size may restrict the generalizability of the results. Furthermore, the study only addressed selected neuromuscular parameters, potentially overlooking other components of athletic performance. Including additional motoric attributes such as agility, reaction time, and balance in future studies would provide a more comprehensive understanding of sport-specific differences. That said, the use of consistent methodology and direct comparisons within this study enhances the reliability of the findings. The results offer practical implications for training design, performance assessment, and talent identification processes. Coaches and performance specialists must evaluate athletes' physical profiles according to sport-specific demands and design individualized training programs accordingly. For example, strength and endurance training for the lower body may be prioritized in football, while upper body strength and anaerobic

power development may be more critical in handball. Furthermore, the test batteries used for talent selection and player development tracking should align with the structural and physiological demands of each sport.

CONCLUSIONS

The present findings highlight distinct physical performance patterns between elite football and handball players, reflecting the sport-specific physiological and biomechanical demands of each discipline. The superior upper body strength observed in handball players aligns with the sport's emphasis on throwing, physical contact, and upper limb coordination, whereas the enhanced lower limb strength in football players may stem from the sport's running-intensive nature and technical demands. Despite these differences, similar outcomes in sprint time, vertical jump, and power output suggest overlapping training effects and convergent adaptations in explosive performance capacities. These observations reinforce the importance of tailoring training and assessment protocols to the unique requirements of each sport. Moreover, while group-level comparisons are informative, individual variability should not be overlooked, especially in high-performance settings. Future research should incorporate broader performance metrics and larger, more diverse samples to deepen our understanding of how anthropometric and neuromuscular attributes interact within and across sporting disciplines.

AUTHOR CONTRIBUTIONS

Conceptualization, Z.I.K., I.I., P.B.; methodology, Z.I.K., I.I.; software, P.B.; validation, Z.I.K., I.I.; formal analysis, Z.I.K.; investigation, I.I.; resources, P.B.; data curation, P.B.; writing—original draft preparation, Z.I.K., I.I., P.B.; writing—review and editing, Z.I.K.; visualization, P.B.; supervision, Z.I.K., I.I.; project administration, Z.I.K.; funding acquisition, P.B. All authors have read and agreed to the published version of the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

INSTITUTIONAL REVIEW BOARD STATEMENT

The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Duzce University (approval number: 2025/74; date: 27.02.2025).

INFORMED CONSENT STATEMENT

Informed consent was obtained from all subjects who were involved in this study.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request and with a valid justification.

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Neuromuscular characteristics of elite and age groups triathletes from world multisport championships

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ABSTRACT

This study aimed to (1) characterize the contractile properties of the main muscles involved in the World Triathlon disciplines; (2) determine to what extent sex and specialization influences neuromuscular characteristics; (3) establish lateral asymmetry profile of athletes' contractile properties. 51 aquathlon, duathlon, cross and long-distance triathletes were assessed through Countermovement Jump (CMJ) and a muscle contractile properties assessment in rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM) and biceps femoris (BF) using tensiomyography prior to the Multisport World Championship. Female triathletes showed a lower CMJ ability than male triathletes in all disciplines ($p = .017$; $\eta^2 = 0.152$), with no differences between disciplines. Females showed a lower contraction time (Tc) in right VM ($p = .014$; $\eta^2 = 0.162$). Small differences were found in contractile properties between disciplines. In conclusion, no significant sex or discipline differences were found in multisport athletes' contractile properties, although women exhibited significant lower jumping ability and greater asymmetry than males in the Tc of the VM. These results provide reference values for different triathlon disciplines that can be of great importance for improving performance and to prevent injuries upon knowing the sport asymmetry profile.

Keywords: Performance analysis, Sports performance, Tensiomyography, Long-distance triathlon, Cross triathlon, Duathlon, Aquathlon.

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INTRODUCTION

Multisport is used to refer to a sport that involves more than one discipline. Since 2017, World Triathlon has launched the Multisport World Championships for professional (elite) and non-professional age-groupers (AG) athletes, bringing together in one venue different discipline such as duathlon (run-bike-run), cross triathlon (swim-mountain bike-trail run), aquathlon (swim-run) and long-distance (LD) triathlon (swim-bike-run). The characteristics and distances of these events are highly variable, ranging from less than 30 minutes in aquathlon, to a minimum of 5 hours in LD triathlon (World Triathlon, 2024).

Despite the growing importance of these modalities, the profile of these athletes has barely been studied. This fact makes it difficult to establish a scientific basis on which are the most influential performance factors in each modality (Lepers and Stapley, 2010). In short distance triathlon, it has been determined that factors such as physiological, neuromuscular, biomechanical, tactical strategy or interaction between disciplines play a fundamental role in performance (Cuba-Dorado et al., 2022). Furthermore, sex-related differences in performance have been described in different modalities and performance levels such as elite and non-elite LD triathletes (Lepers, 2019, Cuba-Dorado et al., 2023), elite cross triathletes (Lepers and Stapley, 2010) or age group duathletes (Romero-Ramos, et al., 2020). However, when performance factors are addressed, women are not usually included in the sample (Lepers, 2019, Barbosa et al., 2019). This fact makes it difficult to reliably understand the physical and physiological characteristics of female triathletes to help them achieve their maximum performance (Lepers, 2019).

Among triathlon performance factors, athletes' neuromuscular profile has not been widely addressed, despite being aware that neuromuscular training adaptations are closely related to performance in any of its disciplines (Cuba-Dorado et al., 2022, Bonacci et al., 2009). Therefore, further research is needed to understand the specific adaptations in response to triathlon training (Bonacci et al., 2009). This neuromuscular profile can be approached from different perspectives: explosive strength with Squat Jump, explosive elastic strength with Countermovement Jump (CMJ) and reflex-elastic-explosive strength assessments with Drop Jump (Loturco et al., 2015, Mueller et al., 2015, Suzuki et al., 2006); muscle electrical activity assessment through Electromyography (Brisswalter et al., 2014, Jacques et al., 2021) or superficial muscle contractile properties assessment using Tensiomyography (TMG).

Tensiomyography assesses muscle contractile properties through the radial deformation of the muscular belly produced by a single electrical stimulus. This is a non-invasive method that does not require physical effort for the athlete. Few studies have characterized well-trained athletes from different triathlon disciplines through TMG, so greater knowledge is essential to effectively interpret the parameters obtained (García-García et al., 2019). Regarding multisport athletes, to our knowledge, it has been used to assess muscle fatigue in non-elite duathletes (Rojas-Valverde et al., 2021) and LD triathletes (Cuba-Dorado et al., 2023, García-Manso et al., 2011). In addition, TMG has also been used to assess lateral asymmetry proven to be an excellent reproducibility tool (Iglesias-Caamaño et al., 2018).

The relationship between lower-limb asymmetries and athletic performance in endurance athletes is complex and multifactorial. Some studies suggest that these asymmetries may negatively impact performance, while others indicate that certain inequalities may not be decisive. In endurance athletes, D'Hondt et al. (2024) reported a negative or non-significant relationship with running performance in most of the asymmetry indicators addressed in their systematic review, except of ankle dorsiflexion, where a more marked effect was observed.

On the other hand, regarding the relationship between lower-limb asymmetries and injury, the scientific evidence remains ambiguous since not all functional tests have the same predictive capacity (Guan et al., 2022). However, there is consensus that differences greater than 10-15% between limbs increase the risk of injury (Impellizzeri et al., 2007, Hamilton et al., 2008). Nevertheless, in response to the subjectivity of these “arbitrary” thresholds, the “specific” thresholds have emerged (Dos’Santos et al., 2021). These new thresholds seek to establish a consensus on the magnitude of asymmetry, favouring each specific sample to apply its specific magnitude of asymmetry. This allows coaches to use these thresholds as reference, criterion, and normative data for specific populations.

Considering the scarce scientific evidence regarding neuromuscular properties of multisport athletes, this study aims to characterize the contractile properties of the main muscles involved in the Multisport World Triathlon disciplines, and to determine to what extent sex and specialization influences neuromuscular characteristics. In addition, establishing lateral asymmetry profile of athletes’ contractile properties.

MATERIAL AND METHODS

Study design

A transversal cross-sectional study design, following an associative strategy was used to assess triathletes’ neuromuscular properties. Triathletes were assessed within 48 h prior to the Multisport World Championship to establish neuromuscular basal values. The testing protocol was carried out in the following order: body composition analysis, TMG and Countermovement Jump. To establish neuromuscular data reliability, six randomly chosen triathletes were evaluated twice.

Participants

Forty-four elite and well-trained AG athletes, who competed in the aquathlon, duathlon, cross-triathlon and LD triathlon 2019 Multisport World Championship composed our sample (Table 1). Following McKay et al.’s (2022) classification based on training volume and performance metrics, our athletes belong to Tiers 3 (Highly Trained/National Level), 4 (Elite/International Level) and 5 (World Class). Written informed consent was obtained from all the athletes included in the study. The research protocol followed the principles of the Declaration of Helsinki regarding biomedical research involving human subjects (64th World Medical Assembly 2013) and had the World Triathlon and the University of Vigo Ethics Committees approval.

Procedure

Countermovement Jump (CMJ)

Countermovement Jump was conducted using the Chronojump BoscoSystem contact platform (Chronojump BoscoSystem®, Barcelona, Spain) instructing the athletes to jump as high as possible while keeping their hands on the hips (Gathercole et al., 2015). Height was calculated by recording flight time through the CHRONOJUMP software (v. 1.7.0 for Windows, Chronojump BoscoSystem®, Barcelona, Spain). This jumping test was selected due to its short-duration and the low-fatigue that could produce competition performance. Moreover, CMJ has been previously related to running economy (Hunter et al., 2015, Paavolainen, 1999, Ramírez-Campillo, 2014), being the run segment part of all the multisport disciplines.

Contractile properties assessment

Vastus Lateralis (VL) and Medialis (VM), Rectus Femoris (RF) and the long head of the Biceps Femoris (BF) from both legs were assessed through TMG following García-García et al.’s (2019) protocol. These four muscles were selected based on their influence in all three triathlon segments (swim, bike, run) and impact on the final outcome. Triathletes were assessed lying on a stretcher following Perotto’s et al. (2005)

anatomical guidelines for sensor placement (GK 30, Panoptik d.o.o., Ljubljana, Slovenia). Two self-adhesive electrodes (5 x 5 cm, Lessa®, AB Medica Group SA, Spain) were placed symmetrically at 5-cm from the digital transducer that applied the progressive electric stimulation in 10-mA steps until reaching the maximal stimulator output (110-mA) (EMF-FURLAN & Co. d.o.o., Ljubljana, Slovenia). The curve with the highest maximum radial displacement for each muscle was included in for analysis. All measurements were carried out by two expert TMG evaluators. The following parameters were recorded: maximum radial muscle belly displacement (Dm) in mm; contraction time (Tc) as the time in ms from 10% to 90% of Dm and radial displacement velocity (Vrd) obtained by the rate ($\text{mm} \cdot \text{s}^{-1}$) between the radial displacement occurring during the period of Tc ($Vrd = (0.8 \times Dm)/Tc \times 1000$).

Analysis

Countermovement Jump and tensiomyography absolute and relative intrarater reliability was calculated through intraclass correlation coefficient (ICC), ICC based on 95% confident interval (IC95%) and coefficient of variation (CV), carrying out a two-way mixed effects model. Sex and specialization (discipline) influence on TMG parameter was assessed with a two-factor ANOVA verifying previously sample's normal and linear distribution through the univariate Kolmogorov-Smirnov test, in conjunction with the Lilliefors test. Homoscedastic assumption was verified with the Box M test followed by a post-hoc HSD Turkey test. Effect sizes in two-way ANOVA were reported as partial eta square (η^2) and interpreted as small (0.01), moderate (0.06), or large (0.14). Statistical significance level was set at $<.05$ alpha. All data were analysed using SPSS v.24.0 for Windows (SPSS Inc., Chicago, IL, USA).

To classify triathletes as “*asymmetrical*”, the specific asymmetry thresholds procedure of Dos'Santos et al. (2021) was followed: $\%Asymmetry + (0.2 \times SD)$. The % of Asymmetry and SD are the average percentage and standard deviation of the sample's asymmetry. This classification was applied individually to each variable of TMG.

RESULTS

The reliability values were ICC = 0.96, IC95% = (0.93-0.99) and CV = 3.1% for Dm; ICC = 0.95, IC95% = (0.90-0.98) and CV = 2.6% for Tc, and ICC = 0.93, IC95% = (0.86-0.96) and CV = 6.1% for CMJ.

The results indicate that female triathletes have much less countermovement jumping ability than male triathletes in all analysed disciplines ($p = .017$; $\eta^2 = 0.152$). However, there are no differences between disciplines (21.19 vs 22.47 vs 21.73 vs 20.90 cm; $p = .835$; $\eta^2 = 0.024$).

Regarding Tc parameter, there are no differences between female and male triathletes (see Table 2), except for the right VM, where female triathletes showed a lower Tc in all assessed muscles ($p = .014$; $\eta^2 = 0.162$) with a large effect size. Regarding differences between disciplines, no differences were found, except cross triathletes that showed a higher Tc in the left BF than standard duathlon triathletes (43.99 ± 3.8 vs 30.71 ± 4.40 ms; $p = 0.03$) and LD triathletes (43.99 ± 3.8 vs 34.19 ± 2.81 ms; $p = .04$) both with a large effect size ($\eta^2 = 0.149$).

Concerning Dm, there are no differences between female and male triathletes, neither in BF nor VM between disciplines. Only the Dm of the right RF from cross triathlon athletes is lower than aquathlon triathletes with a large effect size (7.97 ± 0.92 vs 11.01 ± 0.88 mm; $p = .017$; $\eta^2 = 0.149$) and the right Dm of the VL from standard duathlon athletes is lower than that of LD triathletes with a large effect size (4.50 ± 0.65 vs 6.62 ± 0.38 mm; $p = .008$; $\eta^2 = 0.187$).

Table 1. Athletes' characteristics based on the Multisport World Championship disciplines (mean $\pm$ SD).

Discipline (distance km)		n	Age	Height*	Body Composition†			Competition Time	Weekly Training
		Total (elite)	(years)	(cm)	Body Mass (kg)	Fat (%)	Muscle mass (kg)	(min)	(h)
Standard duathlon (10-40-5)	Female	2 (1)	33.50 $\pm$ 16.26	166.00 $\pm$ 0.71	54.05 $\pm$ 0.92	16.25 $\pm$ 1.63	42.95 $\pm$ 1.49	140.52 $\pm$ 23.97	16.50 $\pm$ 12.02
	Male	4	38.75 $\pm$ 8.77	173.50 $\pm$ 5.02	71.05 $\pm$ 7.34	10.75 $\pm$ 6.40	59.93 $\pm$ 1.92	138.75 $\pm$ 16.39	18.25 $\pm$ 11.35
	Total	6 (1)	37.00 $\pm$ 10.32	171.00 $\pm$ 5.50	65.38 $\pm$ 10.47	12.58 $\pm$ 5.76	54.26 $\pm$ 8.92	140.05 $\pm$ 16.80	16.20 $\pm$ 10.85
Cross triathlon (1-30-7)	Female	3 (3)	25.67 $\pm$ 9.87	156.90 $\pm$ 3.26	51.33 $\pm$ 2.67	15.50 $\pm$ 2.95	41.23 $\pm$ 3.51	143.63 $\pm$ 4.23	19.00 $\pm$ 4.00
	Male	4 (3)	27.00 $\pm$ 7.52	180.70 $\pm$ 6.68	69.28 $\pm$ 7.80	7.28 $\pm$ 2.62	61.15 $\pm$ 8.32	124.17 $\pm$ 12.59	18.50 $\pm$ 4.44
	Total	7 (6)	26.43 $\pm$ 7.83	170.50 $\pm$ 13.70	61.59 $\pm$ 11.17	10.80 $\pm$ 5.06	52.61 $\pm$ 12.33	132.51 $\pm$ 13.91	18.71 $\pm$ 3.90
Aquathlon (1-5)	Female	3 (3)	20.33 $\pm$ 0.58	165.93 $\pm$ 8.50	59.00 $\pm$ 5.20	17.53 $\pm$ 3.75	46.23 $\pm$ 5.38	35.54 $\pm$ 1.59	26.50 $\pm$ 7.78
	Male	5 (2)	31.40 $\pm$ 7.86	179.32 $\pm$ 1.17	75.62 $\pm$ 8.98	10.40 $\pm$ 5.12	64.18 $\pm$ 6.11	37.12 $\pm$ 11.33	19.40 $\pm$ 3.78
	Total	8 (5)	27.25 $\pm$ 8.26	174.30 $\pm$ 8.33	69.39 $\pm$ 11.30	13.08 $\pm$ 5.71	57.45 $\pm$ 10.26	36.44 $\pm$ 8.11	21.43 $\pm$ 5.62
Long distance (1.5 $\pm$ -113-30)	female	5 (2)	36.80 $\pm$ 9.47	165.42 $\pm$ 6.13	57.44 $\pm$ 5.25	16.52 $\pm$ 4.91	45.38 $\pm$ 3.36	466.64 $\pm$ 83.73	19.80 $\pm$ 8.17
	Male	18 (2)	36.17 $\pm$ 8.12	176.48 $\pm$ 5.43	71.74 $\pm$ 6.96	10.21 $\pm$ 3.89	61.08 $\pm$ 5.20	418.77 $\pm$ 46.84	15.94 $\pm$ 4.34
	Total	23 (4)	36.30 $\pm$ 8.28	174.07 $\pm$ 7.17	68.63 $\pm$ 8.88	11.57 $\pm$ 4.81	57.67 $\pm$ 8.17	429.65 $\pm$ 58.56	16.82 $\pm$ 5.46
Total	Female	13 (9)	29.92 $\pm$ 10.84	163.66 $\pm$ 6.43	55.87 $\pm$ 4.91	16.48 $\pm$ 3.55	44.25 $\pm$ 3.86	242.44 $\pm$ 195.47	19.73 $\pm$ 7.68
	Male	31 (7)	34.55 $\pm$ 8.54	177.10 $\pm$ 5.33	71.96 $\pm$ 7.28	9.93 $\pm$ 4.24	61.44 $\pm$ 5.40	286.87 $\pm$ 166.44	17.17 $\pm$ 5.47
	Total	44 (16)	33.18 $\pm$ 9.40	173.13 $\pm$ 8.35	67.21 $\pm$ 9.94	11.86 $\pm$ 5.02	56.36 $\pm$ 9.35	273.12 $\pm$ 174.74	17.85 $\pm$ 6.14

Note. *Height was measured through a stadiometer (Seca 213, Seca gmbh & co. kg., Hamburg, Germany). †Body composition was analysed through a Bioelectrical Impedance Analysis (Tanita MC-780MA, Tanita Corporation, Tokyo, Japan). ‡ The original 3-km swim segment was shortened following World Triathlon regulations due to low water and air temperature.

Table 2. Descriptive statistics of neuromuscular variables based on sex and discipline.

Parameter	Standard duathlon		Cross triathlon		Aquathlon		LD triathlon	
	Female	Male	Female	Male	Female	Male	Female	Male
CMJ	20.63 ± 0.65	21.76 ± 3.62	20.49 ± 2.02	24.45 ± 3.20	20.09 ± 3.14	23.37 ± 6.26	17.97 ± 3	23.82 ± 3.96
Tc BF right	32.13 ± 0.24	31.56 ± 4.3	44.27 ± 14.6	34.77 ± 6.63	39.04 ± 10.3	34.18 ± 8.98	31.09 ± 3.45	39.07 ± 13.8
Tc BF left	28.34 ± 0.5	33.08 ± 8.59	44.44 ± 18.09	43.55 ± 15.7	35.10 ± 7.57	35.64 ± 5.43	31.77 ± 2.33	36.61 ± 10.1
Tc RF right	29.88 ± 0.02	30.88 ± 10.7	23.16 ± 2.08	30.34 ± 4.67	25.05 ± 0.90	29.44 ± 3.06	26.59 ± 1.08	29.21 ± 5.56
Tc RF left	29.87 ± 3.25	27.77 ± 4.14	25.15 ± 1.69	28.14 ± 5.95	28.54 ± 3.27	28.55 ± 3.95	25.57 ± 4.27	29.07 ± 4.72
Tc VL right	22.91 ± 0.00	22.89 ± 2.44	24.15 ± 3.77	25.41 ± 4.96	20.55 ± 1.99	25.66 ± 2.29	22.81 ± 1.84	24.43 ± 3.63
Tc VL left	22.26 ± 0.13	23.14 ± 2.31	23.00 ± 1.38	24.82 ± 4.36	22.99 ± 2.42	24.44 ± 0.77	20.99 ± 1.18	24.86 ± 3.77
Tc VM right	22.11 ± 0.36	23.68 ± 1.94	23.07 ± 2.05	23.80 ± 3.62	19.55 ± 1.22	23.53 ± 1.07	21.54 ± 0.84	23.43 ± 2.30
Tc VM left	25.08 ± 4.12	25.18 ± 1.40	24.13 ± 1.41	23.39 ± 3.82	23.55 ± 1.73	23.22 ± 1.25	21.27 ± 1.58	23.34 ± 2.03
Dm BF right	7.72 ± 0.43	6.86 ± 2.33	10.73 ± 1.66	7.17 ± 0.86	7.09 ± 1.65	9.03 ± 2.89	8.52 ± 3.25	8.09 ± 1.87
Dm BF left	7.85 ± 1.15	7.64 ± 2.61	8.80 ± 1.71	7.79 ± 1.07	7.68 ± 0.38	8.76 ± 3.55	7.61 ± 3.29	8.12 ± 1.69
Dm RF right	9.78 ± 1.19	8.51 ± 4.77	6.76 ± 2.46	9.17 ± 2.50	10.84 ± 2.88	11.18 ± 1.46	9.24 ± 1.05	8.74 ± 2.08
Dm RF left	7.64 ± 0.57	8.60 ± 4.42	6.79 ± 0.57	9.08 ± 1.76	8.45 ± 2.84	8.77 ± 2.09	8.36 ± 1.65	8.68 ± 2.31
Dm VL right	4.05 ± 0.34	4.95 ± 1.32	5.52 ± 1.42	6.98 ± 1.95	5.33 ± 1.15	6.13 ± 1.12	6.95 ± 0.5	6.29 ± 1.76
Dm VL left	4.62 ± 1.44	5.18 ± 1.51	5.89 ± 1.63	7.44 ± 2.15	6.20 ± 0.90	6.22 ± 2.23	6.61 ± 1.11	6.42 ± 1.52
Dm VM right	7.82 ± 1.40	7.15 ± 1.08	7.09 ± 0.61	8.20 ± 0.97	6.86 ± 1.22	8.33 ± 1.93	7.27 ± 2.15	8.46 ± 1.32
Dm VM left	6.51 ± 1.22	7.23 ± 1.34	7.80 ± 1.58	8.81 ± 1.30	8.60 ± 2.16	7.89 ± 2.19	6.99 ± 1.53	8.23 ± 1.78
Vrd BF right	192.2 ± 12.3	171.9 ± 46.1	203.2 ± 47.4	167.6 ± 23.4	149.3 ± 32.6	208.9 ± 19.2	216.1 ± 67.7	175.9 ± 47.8
Vrd BF left	221.3 ± 28.8	181.9 ± 23.2	170.2 ± 44.2	153.3 ± 39.9	180.1 ± 34.9	191.0 ± 64.9	188.0 ± 66.9	184.0 ± 43.6
Vrd RF right	261.9 ± 31.7	211.7 ± 87.1	231.2 ± 69.3	238.1 ± 32.6	348.8 ± 103.7	304.8 ± 35.3	278.5 ± 72.7	241.9 ± 53.0
Vrd RF left	206.6 ± 38.0	240.7 ± 101.1	216.4 ± 17.3	259.6 ± 18.4	243.2 ± 104.6	244.2 ± 46.0	265.9 ± 66.8	240.9 ± 61.4
Vrd VL right	141.5 ± 12.1	172.2 ± 37.2	183.8 ± 44.6	220.5 ± 49.3	207.1 ± 38.2	193.5 ± 45.4	246.1 ± 37.4	207.3 ± 52.7
Vrd VL left	166.3 ± 53.0	177.6 ± 36.6	203.5 ± 46.2	235.8 ± 32.7	215.2 ± 13.7	204.0 ± 73.8	252.1 ± 40.4	208.3 ± 46.0
Vrd VM right	282.3 ± 45.9	241.9 ± 34.1	246.3 ± 16.1	282.2 ± 61.8	280.5 ± 41.8	284.2 ± 68.0	268.0 ± 72.0	290.7 ± 50.3
Vrd VM left	207.3 ± 4.9	228.9 ± 34.1	261.1 ± 68.4	305.5 ± 48.7	292.6 ± 72.6	271.8 ± 75.3	266.9 ± 78.3	284.6 ± 70.4

Note. LD (long distance); CMJ (height of countermovement jump, in cm); Tc (contraction time, in ms); BF (biceps femoris); RF (rectus femoris); VL (vastus lateralis); VM (vastus medialis); Dm (maximum radial muscle belly displacement, in mm); Vrd (radial displacement velocity, in mm·s⁻¹).

In relation to Vrd, there are no differences between female and male triathletes either (see Table 2). Neither BF nor VM show differences between disciplines. On the contrary, the right RF of aquathlon triathletes is much faster ($321.37 \pm 65.64 \text{ mm}\cdot\text{s}^{-1}$) than that of duathlon triathletes ($228.45 \pm 73.73 \text{ mm}\cdot\text{s}^{-1}$) and LD triathletes ($248.60 \pm 51.80 \text{ mm}\cdot\text{s}^{-1}$) with a large effect size ($\eta^2 = 0.255$). In addition, both VLs are slower in standard duathlon athletes than in LD triathletes with a large effect size (right 156.84 ± 20.37 vs $226.78 \pm 11.89 \text{ mm}\cdot\text{s}^{-1}$; $p = .005$; $\eta^2 = 0.200$; left 171.98 ± 20.37 vs $230.22 \pm 13.00 \text{ mm}\cdot\text{s}^{-1}$; $p = .021$; $\eta^2 = 0.146$).

No differences were observed in the magnitude of lateral asymmetries of BF, RF and VL between male and female triathletes, or between disciplines. On the contrary, female triathletes have a greater asymmetry than male triathletes in the Tc of the VM (9.89 vs 5.26% ; $p = .006$) with a large effect size ($\eta^2 = 0.197$). In addition, Tc asymmetry of the VM is lower in cross triathletes (3.18%) than Duathlon triathletes (9.20% , $p = .039$) and aquathlon triathletes (10.64% , $p = .006$) with a large effect size ($\eta^2 = 0.213$).

In relation to lateral asymmetry direction of the VM, both men and women was towards non-dominant limb, being this limb the one with the highest Tc and the dominant limb the one with the lowest Tc in VM. Likewise, the asymmetry of the Tc of the VM in cross, duathlon and aquathlon triathletes was towards non-dominant limb.

Specific asymmetry thresholds categorize triathletes as “*asymmetrical*” when their lateral asymmetry in muscle contractile properties of BF was greater than 33.6% in Dm, 25.6% in Tc and 49.5% in Vrd. Only 5.9% , 5.9% and 3.9% (respectively) of the triathletes were categorized asymmetrical. Triathletes were classified as asymmetrical in RF when lateral asymmetry exceeded 14.1% for Tc, 39.5% in Dm and 38.9% in Vrd. A 21.6% for Tc, 3.9% for Dm and 3.9% for Vrd of the triathletes were asymmetrical. Triathletes were classified as asymmetrical in VL when lateral asymmetry exceeded 6.5% for Tc, 34.6% in Dm and 30.2% in Vrd. A 39.2% for Tc, 3.9% for Dm and 11.8% for Vrd of the triathletes were asymmetrical. Finally, triathletes were classified as asymmetrical in VM when lateral asymmetry exceeded 8.1% for Tc, 30.1% in Dm and 27.6% in Vrd. A 33.3% for Tc, 9.8% for Dm and 9.8% for Vrd of the triathletes were asymmetrical.

DISCUSSION

The main findings of this study indicate that female triathletes have much lower CMJ ability than male triathletes in all the analysed disciplines. However, few significant sex-differences were found between female and male contractile properties, and World Triathlon disciplines.

Our sex-differences in CMJ performance are in line with previous reference power values for jump squat for endurance athletes (long distance runners and triathletes), showing considerably lower values for females than males (Valenzuela et al., 2020).

Regarding contractile properties, very few sex-differences were obtained between triathletes. Females' Tc of the left VM was lower than males in all World Triathlon disciplines, with female triathletes also showing greater lateral asymmetry than males in Tc of the VM. The meagre sex-differences found in contractile properties does not resemble with the performance differences reported by other authors (Lepers, 2019, Lepers and Stapley, 2010, Barbosa et al., 2019), therefore sex-differences in performance are explained by other factors. Lepers and Stapley (2010) have pointed out sex-differences in cross triathlon performance, especially in the cycling segment, suggesting that cycling technical characteristics can have a direct influence in type of races, encouraging the exploration of physiological factors that may influence performance. However, contractile properties do not seem to be one of them. Neither seem to have any influence in LD triathlon where the

technical component is lower and where sex-differences, despite having been considerably reduced over the years, are still present (Lepers, 2019). These findings are similar to those found in other sports such as canoeing, where barely sex-differences in muscle contractile properties were reported (Álvarez-Yates et al., 2024a). This reinforces the idea that muscular physiological properties are common and independent of sex (Staron et al., 1994).

Concerning the analysis between World Triathlon disciplines, no differences were found in the CMJ between disciplines, however few differences were shown in contractile properties. This may be because Olympic-distance triathletes often race in other disciplines over the season. The main contractile properties differences were found in cross triathletes, showing a higher Tc in the left BF than duathletes and LD triathletes, and a lower Dm in the right RF than aquathlon athletes. These results are in line with García-Manso et al. (2011) that found Tc values in the left BF greater than the double of the right BF in LD triathletes, however in our results LD triathletes do not show such difference. In addition, our duathlon athletes exhibited a lower Dm in the right VL and a lower Vrd in both right and left VL than LD triathletes, while aquathlon athletes showed a higher Vrd in the right RF than duathletes and LD triathletes. Nevertheless, it should be noted that the Dm of the RF of aquathlon athletes, of both female and male, turned to be greater than the other analysed disciplines. If we compare these values with well-trained cyclists (García-García et al., 2013, 2018), aquathlon athletes' Dm values in RF are still much higher than cyclists. Therefore, it would be interesting to analyse whether not performing the cycling segment in these athletes can influence a lower muscle tone in this musculature. Finally, the lateral asymmetry of the Tc in VM was lower in cross triathletes than duathlon and aquathlon athletes.

To our knowledge, this is the first study that attempts to characterize the different triathlon modalities at the neuromuscular level. When comparing contractile properties values with athletes from similar movement patterns to triathlon, it can be noted that our triathletes' average Tc value from the VM and RF are lower than cyclist values reported by García-García et al. (2013, 2018), both during preparatory and competition period. Similarly, the average Tc value from the VL in all analysed disciplines is slightly lower than mountain marathon runners reported by Giovanelli et al. (2016). Regarding the Tc values of BF from our results, these are similar to cyclists (García-García et al., 2013, 2018) except for the left leg of cross triathletes' which showed greater values. However, if we compare our results with those obtained with LD triathletes by García-Manso et al. (2011) we can observe that all average values are lower than their average left BF, and higher than the right BF.

Furthermore, high intensity training decreases muscle contraction time (Tc), specifically in those involved in training (Šimunič, 2011). Therefore, athletes from sports that require greater strength and power, are usually characterized by lower Tc than endurance athletes (García-García et al., 2019). Accordingly, it is not unreasonable to think that specialized athletes in different triathlon modalities may present higher Tc values than athletes that require speed strength due to their sports characteristics. Comparing our data with other sports, it is noted that our male knee extensor muscles values (RF, VL and VM) are within males' soccer players values (García-García et al., 2019) and similar to male acrobatic gymnastics (Vernetta-Santana et al., 2018), and beach volleyball players (Rodríguez-Ruiz et al., 2012), the latter showing higher values in VM. Greater values are also found in the Tc of RF in tennis players (Wiewelhove et al., 2017) and tumbling gymnasts (Rojas-Barrionuevo et al., 2016) however showing the latter lower values in VL and VM. Regarding women knee extensor muscles values, duathlon athletes' VL, VM and RF values are similar to female rugby players (Valenzuela et al., 2018), although our RF values from other World Triathlon disciplines are slightly lower, as well as female beach volleyball players (Rodríguez-Ruiz et al., 2012). When comparing our data with female soccer players, their Tc values of RF are lower than all World Triathlon disciplines, except for

duathlon athletes (Paravlic et al., 2022). Nevertheless, when comparing BF, female LD triathletes show higher Tc than female soccer players (Paravlic et al., 2022), while cross triathletes and aquathlon athletes showed higher Tc than beach volleyball players (Rodríguez-Ruiz et al., 2012). Male LD triathletes also showed higher values male soccer players (Fernández-Baeza, 2025) and beach volleyball players (Rodríguez-Ruiz et al., 2012). Although, when compared with acrobatic gymnasts, data differs considerably depending on the discipline (Vernetta-Santana et al., 2018). In brief, female and male triathletes, exhibit slower Tc value from the BF than other acyclic sports athletes, although showing similar quadriceps muscles values (RF, VL and VM). Even though these sports are performed at very different intensities, the high correlation between Tc and the percentage of type I fibres (Dahmane et al., 2001) together with the maximum TMG output stimulation (110 mA), could be a limitation for stimulating large motor neurons, which are more characteristic in high-intensity sports (García-García et al., 2019).

Regarding radial muscle belly displacement (Dm), our BF values, from all Word Triathlon disciplines, are higher than LD triathletes reported by García-Manso et al. (2011) and cyclists analysed by García-García et al. (2013). However, these are similar to García-García et al.'s (2018) cyclists, except for female cross triathletes and male aquathlon athletes that are higher. Male cross triathlon exhibited higher Dm in RF, VL and VM than cyclists (García-García et al., 2013, 2018), and in VL than mountain runners (2016). Female LD triathletes showed greater Dm values in left RF than cyclists (García-García et al., 2013, 2018) and left VL than cyclists (García-García et al., 2013, 2018) and mountain runners (Giovannelli et al. 2016), and a lower Dm in left VM than cyclists (García-García et al., 2013, 2018). Duathlon athletes also showed a lower Dm in VL than cyclists in both legs and a higher Dm in right RF. Moreover, regarding Aquathlon, besides the RF differences with cyclists, women also showed higher Dm values in VM than male cyclists. The remaining Dm values are in the same range as cyclists, mountain runners and long-distance triathletes.

Low values in Dm have been associated with greater muscle-tendon stiffness (Pišot, 2008), therefore, athletes who require speed strength usually present lower values in this parameter (García-García et al., 2019). Female triathletes show greater Dm in BF than beach volleyball players (Rodríguez-Ruiz et al., 2012), although there is no clear pattern in relation to knee extensors Dm when comparing with rugby players (Valenzuela et al., 2018), beach volleyball players (Rodríguez-Ruiz et al., 2012) or soccer players (Paravlic et al., 2022). Respecting males, our triathletes' Dm was higher in all analysed muscles than bodyboarders (Rodríguez-Matoso, et al. 2015), while the knee extensors showed lower or similar values to tumbling (Rojas-Barrionuevo et al., 2016), tennis (Wiewelhove et al., 2017), acrobatic gymnastics (Vernetta-Santana et al., 2018) or beach volleyball athletes, except for the VL (Rodríguez-Ruiz et al., 2012). Regarding males' BF, higher Dm values were obtained from our triathletes than soccer player (Fernández-Baeza, 2025), volleyball players (Rodríguez-Ruiz et al., 2012) and abovementioned bodyboarders (Rodríguez-Matoso, et al. 2015); although lower than acrobatic gymnasts (Vernetta-Santana et al., 2018). Therefore, Dm behaviour seems to be related to Tc when comparing sports, since quadriceps muscles (RF, VL and VM), both male and female triathletes, exhibit similar, or even lower, values than to other acyclic sports athletes. However, triathletes' BF seems to show a lower muscle tone than other sports, except gymnastics.

Concerning to lateral asymmetry, the main distinguishing characteristic observed was in Tc of VM, showing females greater asymmetry than males. These values seem to indicate that the non-dominant leg may be the limb with the highest Tc, since the stronger leg would be determined as dominant due to its greater running impulse in endurance athletes. However, this suggests the need to investigate whether the sports movements biomechanics involved in this activity can explain this.

On the other hand, no major asymmetries were found after applying Dos'Santos et al. (2021) "specific" thresholds. The percentage of asymmetrical athletes for the Tc of RF, VL, and VM, was 21.6 %, 39.2 % and 33.3%, respectively. Regarding the remaining parameters, only the Vrd of VL stands out, with 11.8 % of asymmetrical classified athletes, while the remaining parameters were lower than 9.8%. When comparing the "specific" threshold with canoeists (Álvarez-Yates et al., 2024b), both females and male, RF and BF thresholds are higher, excepting the Tc of BF (25.53%). Similarly, the percentage of asymmetrical athletes in volleyball players was higher for the Dm of BF (30.44%) and slightly lower for Dm of RF (30.12%) (Iglesias-Caamaño et al., 2022).

Overall, the results obtained in this study can help athletes from different triathlon disciplines to determine whether their neuromuscular properties meet the reference values for their discipline. This is of great importance to enhance performance through training and to prevent injuries upon knowing the sport asymmetry profile. In this sense, future lines of research should relate asymmetry thresholds to competitive performance to determine whether triathletes with the highest performance present an asymmetric profile, as occurs in other sports. Likewise, it may be of great interest to understand whether the detected asymmetries are related to injuries risk. In any case, the main limitation of this study is the small sample size of each triathlon discipline, so the results should be viewed with caution. However, to our knowledge, this is the first study to establish reference values for triathletes using a sample of high-performance athletes.

CONCLUSIONS

In conclusion, there are no significant sex or discipline differences in multisport athletes' contractile properties, although women exhibited a significant lower jumping ability than men, with no significant differences between World Triathlon disciplines. Furthermore, there are no substantial differences in knee extensor muscles properties (Tc and Dm) between triathlon disciplines, however, triathletes exhibiting slower contraction time in BF than other sports. Finally, no sex or discipline differences were observed in the magnitude of lateral asymmetries of BF, RF and VL, only showing females a significant greater asymmetry than males in the Tc of the VM.

AUTHOR CONTRIBUTIONS

Alba Cuba-Dorado: conceptualization, methodology, software, investigation, resources, data curation, writing, review, and project administration. Tania Alvarez-Yates: methodology, investigation, writing, and review. Mario Iglesias-Caamaño: formal analysis, investigation, and writing. Javier Carballo-Lopez: software, and investigation. José Manuel Abalo-Rey: investigation. Alicia Riveiro-Bozada: investigation. Tania García-Remeseiro: investigation, and resources. Oscar García-García: conceptualization, methodology, formal analysis, investigation, resources, writing, review, and project administration. All authors have approved the manuscript and agree with its submission to JHSE.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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Motivation analysis in rugby: A systematic review

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ABSTRACT

Rugby is a sport that requires a high combination of physical and mental abilities, so athletes' motivation is a key factor in improving performance and sustainability participation. This systematic review examines a range of studies that address motivation in rugby from both intrinsic and extrinsic perspectives, as well as how social and cultural contexts affect player motivation. The studies analysed included aspects of athlete leadership, social identity, inspiring communication, emotional intelligence training, and barriers and facilitators in the implementation of injury prevention programs. The findings show that strong motivation, effective leadership, team solidarity, and social environment support play a positive role in improving rugby athletes' long-term performance and engagement. Recommendations are given for the development of training programs and motivation management strategies that take into account psychological, social, and structural dimensions so that performance development can run sustainably.

Keywords: Athlete motivation, Rugby, Sports leadership, Social identity, Emotional intelligence.

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INTRODUCTION

Rugby is a sport that demands high physical and mental skills, so the players must have strong motivation (Mellalieu, 2017). Motivation is a key factor that greatly affects the performance and success of athletes in undergoing training and matches (Bandhu et al., 2024). Without sufficient motivation, it is difficult for players to reach their best potential and be consistent in training and competing (Sandars et al., 2022). In addition, motivation also plays an important role in shaping the attitude and work ethic of rugby players (Fioravanti et al., 2023). A good attitude and a spirit of hard work support the development of essential technical and tactical skills in this sport. With continued motivation, athletes can develop their abilities optimally and maintain their commitment so that they can compete at a higher level.

Motivation in rugby athletes can be understood through two main dimensions, namely intrinsic and extrinsic motivation (J. Pope & Wilson, 2012). Intrinsic motivation is related to the impulses that come from within the athlete himself, such as pleasure, personal satisfaction, and a sense of achievement that the athlete feels (Almagro et al., 2020). Intrinsically motivated athletes usually have a high passion for continuing to train and compete because they truly enjoy the processes and challenges that exist in the sport. On the other hand, extrinsic motivation comes from external factors that affect athletes, such as professional expectations, financial rewards, social support from family and friends, and the influence of coaches (Pelletier et al., 2016). These factors can provide an additional incentive for athletes to excel and maintain commitment in training and competition.

Coaches play a crucial role in shaping and increasing the motivation of rugby players (Malkin et al., 2025). Through the leadership style they apply as well as the approach used during training, coaches can influence the player's internal enthusiasm and drive to improve (Berg & Karlsen, 2020). An effective leadership style is able to create a supportive training environment, provide clear direction, and build player confidence, thus fostering intrinsic motivation that motivates players to practice and compete optimally (Baker et al., 2016). The relationship between a coach's leadership style and player motivation has a significant impact on performance on the field (Jin et al., 2022). High intrinsic motivation, influenced by the right leadership style, directly contributes to improved performance and match results (Xue et al., 2022). Therefore, an in-depth understanding and systematic study of how a coach's leadership style can improve player motivation is very important in the effort to achieve the best performance in rugby.

Social and cultural backgrounds play an important role in shaping the motivation of rugby athletes, especially at school and community level (Zainuddin et al., 2023). In a variety of contexts, the motivation to play rugby is not only driven by physical or competitive aspects, but also by inherent social values such as the desire to show courage (J. Pope & Wilson, 2012). Additionally, the identity aspect of masculinity is often a factor that influences one's passion and reasons for getting involved in the sport, as rugby is often seen as a symbol of strength and courage associated with a male image (Diamond, 2006). Furthermore, group solidarity is also an important element that motivates rugby athletes (Branchu, 2023). A sense of community and team spirit within the community or school creates a strong bond, thus encouraging athletes to keep participating and keep trying. A comprehensive and systematic method is needed to explore various internal elements such as self-confidence and personal goals, as well as external elements such as the influence of the social and cultural environment, so that athletes' motivations can be understood thoroughly and effectively.

Through a systematic review of the literature, this study aims to collect and analyse the existing evidence related to motivation in rugby in order to formulate a solid theoretical and practical framework. The results are expected to make a significant contribution to coaches, athletes, and sports policy developers in creating

a training environment that maximizes motivation. Thus, the development of performance and the sustainability of participation in rugby can be realized more effectively and sustainably.

METHODS

The preparation of this article was carried out through systematic analysis using the literature review method. A comprehensive strategy is designed to collect and evaluate research results related to motivation analysis in rugby. This approach ensures the identification of methodologically rigorous relevant sources, with a focus on the synthesis of the latest scientific findings. The literature search was conducted using a specific keyword combination: TITLE-ABS-KEY (Motivation AND Rugby). This strategy is applied to screen documents that explicitly address the target topic. The main database used is Scopus, chosen for its multidisciplinary scope and reputation in an index of high-quality scientific works. The inclusion criteria include articles that discuss motivation analysis in rugby as a core topic. In contrast, the exclusion criterion negates publications outside the last 10-year span (2016–2025). This time constraint ensures up-to-date evidence-based analysis, while maintaining the relevance of findings to the latest scientific context. The research limits the subject to three main areas: medicine, social sciences, health professions, psychology. Only English-language journal articles are included in the analysis, with document types limited to Articles (not books, reports, or non-standard materials). This filtering maintains the focus and consistency of the data source. The study follows PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and reproducibility. Each stage starts from searching, filtering, to detailed documentation synthesis to minimize bias and increase the validity of the final conclusion.

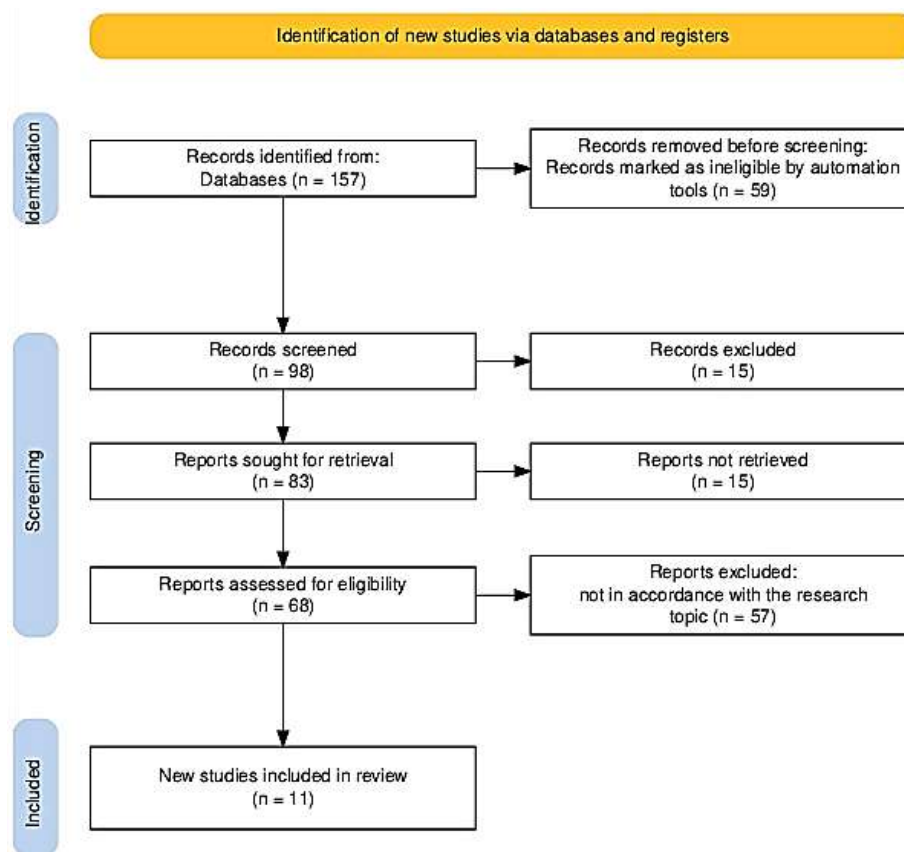


Figure 1. Prisma follow chart.

RESULTS

Table 1. Summary of review article.

No.	Author	Research objectives	Research methods	Research results
1.	(Fransen et al., 2017)	To examine the extent to which the perceived leadership qualities of athletes relate to the effectiveness of elite sports teams. It also aims to identify the leadership structure and the relationship between athlete leadership qualities and team effectiveness.	Design: Observational/correlation studies. Participants: Three professional rugby teams (N = 135) in Australia. Data Collection: An online survey asked players and coaching staff to assess the leadership qualities of players in four roles (task, motivation, social, external). Leadership quality is calculated using social network analysis (SNA) based on the indegree centrality of the top three leaders in each role. Participants also rated their team's performance and functioning. Data Analysis: Statistical analysis for the relationship between leadership quality and team effectiveness indicators.	The team with the highest quality athlete leadership excels in all indicators of team effectiveness. Athletes on these teams have a stronger sense of team purpose, are more committed to team goals, and have greater confidence in their team's abilities. The team also exhibits a more task-oriented climate (players support each other to thrive) and a less ego-oriented climate (less conflict). The team performed well in measures of performance reported by players, coaches, and objectives. High-quality athlete leadership is positively related to team effectiveness. This study highlights the need for well-planned and empirical leader development programs.
2.	(Cheng et al., 2016)	To explore the involvement of older male amateur rugby players in Taiwan, why they continue to play, how they view their experiences, and how the sport evolved to sustain their interests. The goal is to implement the concept of "serious leisure".	Design: A qualitative research approach using semi-structured interviews. Participants: The sample was aimed at 15 male amateur rugby players aged 54 to 83 years from a "golden oldie" rugby club in Taiwan. Data Collection: Semi-structured qualitative interviews in 2013, audio recorded and verbatim transcribed. Data Analysis: Thematic analysis uses a six-phase approach.	The main motivations to keep playing are: a sense of nostalgia and pride, a lifelong friendship and sense of belonging, as well as pure joy and passion. Secondary motivations include: staying mentally and physically active, involvement in "true men's sports", maintaining self-identity, and responsibility/commitment to sport. Long-term engagement is consistent with the concept of "serious leisure". A strong sense of responsibility, commitment and identification with rugby are key motivators for continued participation and a desire to promote the game to the younger generation.
3.	(Campo et al., n.d.)	To test the influence of identity mechanisms (personal identity vs. social identity) on the assessment process, in particular whether the level of self-abstraction leads to group-based emotions and influences performance in team sports. It is also to examine the influence of individual emotions and emotions that refer to the team on performance after controlling the identity process.	Design: Experimental design Participants: 30 elite male rugby players (Mage = 19.06 years) from the same U21 team, randomly divided into two teams. Procedure: A 30-minute competitive rugby union match is held to reproduce the official match conditions. Data Collection: Individual and team-level emotions felt (10-cm VAS scale) and performance were measured 17 times during the match. Performance is judged by elite coaches who watch video footage. Data Analysis: Chi-square test for emotion frequency, Linear Mixed Effects (LME) model for emotion intensity and performance.	High levels of self-abstraction (social identity conditions) lead to individual emotions and emotions that refer to more positive and intense teams, as well as less frequent negative emotions. After controlling self-abstraction, only positive emotions refer to the team that positively affect the performance of the individual and the team. Individual emotions have no significant effect on performance. The group of social identity conditions performed better and won 17-0. Individual performance in the personal identity condition decreases over time, while in the social identity condition it increases smoothly. This study suggests that social identity and its relationship to emotions that refer to teams can be a key dimension of the emotional-performance relationship in team sports. Coaches are advised to build a team identity to avoid negative emotions and facilitate positive emotions that refer to the team to improve performance.
4.	(Kerr, 2015)	To examine the motivational nature of participation to start and continue playing rugby among Canada's elite women's rugby union players. The secondary goal is to highlight their experience in full-contact sports that has historically been unavailable to women.	Design: The qualitative research methodology uses inductive thematic analysis, interpreted through reversal theory. Participants: Snowball samples from 10 Canadian international level elite women's rugby players. Data Collection: Semi-structured interviews are open (8 face-to-face, 2 phone). The interview is audio recorded and transcribed verbatim. Data Analysis: Inductive thematic analysis, followed by interpretation through reversal theory.	The motivation for participation is multifaceted, with motives changing and evolving over time, especially as players reach elite levels. Four main participation motivational themes and seven sub-themes were identified: Getting a good start with rugby; Physical aspects (physical and aggression; physical challenges); Achievements and successes (learning a new sport; a sport that suits my body type); and Player interaction on and off the field (team-mates/team environment; friendship and rugby community; being non-conformist). Pleasure from the physical and aggressive aspects are the main motives, but achievement, skill mastery, and achievement/survival at the elite level are also strong motives. These findings can inform sports psychologists and administrators (e.g., developing a positive team climate, promoting women's rugby with a focus on various aspects of interest).

5.	(Koutrou & Downward, 2016)	To explore the potential utilization of volunteering activities in a variety of contexts as a result of previous sports club volunteering experiences and to establish what determines the decision to volunteer and continue to volunteer. Addressing three key issues: identifying the effects of different factors on voluntary decision-making, examining whether involvement in one sport volunteering context stimulates further volunteering, and commenting on actions for governments/NGBs in realizing " <i>Big Society</i> " through sport volunteering.	Design: Survey-based study, using regression analysis. A case study of women's rugby union in England. Participants: 168 volunteers involved in women's rugby in England completed a web-based survey. The sample size for regression analysis was 131. Data Collection: Web-based survey prior to the 2010 Women's Rugby World Cup (WRWC). Post-event audits identify actual WRWC volunteers. Variables included socio-demographic characteristics, previous sports involvement, motivation, and satisfaction with volunteering. Data Analysis: Factor analysis to summarize volunteer satisfaction. Regression analysis (logistics and OLS) to identify impacts on actual WRWC volunteering and future volunteering intentions.	Supporting the transfer of volunteer efforts between activities. Factors influencing actual WRWC volunteering: Satisfaction with volunteer roles, communication within the club, being playing rugby, meeting the needs of others (altruism), having free time, British white ethnicity, and higher education. Full-time employment and student status reduce the possibilities. Poor satisfaction with the club's experience is a common determinant of volunteering at the WRWC or other rugby/sporting events, indicating the substitution of effort. The study highlights the potential of sports governing bodies to recruit existing club volunteers for events, and for the transfer of activities between sports. It supports the " <i>Big Society</i> " agenda.
6.	(Koutrou & Downward, 2016)	To explore the potential utilization of volunteer activities in a variety of contexts as a result of previous single sporting event experiences, and to determine what factors influence future volunteer decisions.	Design: Women's Rugby World Cup (WRWC) 2010 case study. Longitudinal survey studies (pre-event and post-event). Participants: 70 WRWC 2010 volunteers completed an online survey. Data Collection: Online survey (pre-event: socio-demographic profile, sport/volunteer experience, motivation; post-event: satisfaction, future intention to volunteer). Data Analysis: Analysis of factors for motivation and satisfaction. Regression analysis (OLS) to identify factors that influence future voluntary intentions.	Ensure multi-dimensional motivation of volunteers (8 factors: Career Orientation, Patriotism & community values, Interpersonal Contact, Recreation, Extrinsic Rewards, Expression of Values, Personal Growth, Love of Rugby). The highest motivation is the Expression of Values and Love of Rugby. Four satisfaction-related factors emerged: Tournament Facilities, Event Organization, Athlete Attitude, and Support to Volunteers. Volunteers report higher satisfaction with Tournament Facilities and Support to Volunteers. Future Volunteer Intentions: Higher education and satisfaction with event experience increase the likelihood of volunteering for similar sporting events in the future. Satisfaction with the WRWC experience increases the intention to volunteer at rugby and other sporting events but can hinder club volunteering. Highlight the potential of voluntary legacy and cross-contextual transfer efforts, emphasizing the role of support networks.
7.	(Chapron & Morgan, 2020)	To investigate how Welsh regional rugby academy head coaches can leverage collaborative action research (CAR) to influence collaboration, learning and pedagogical change within coaching groups.	Design: Collaborative Action Research (CAR) is practical. The process of planning cycles, data collection, analysis, reflection, and change. Participants: The principal investigator (Head Coach of the Welsh regional rugby academy) collaborated with two other professional rugby coaches and two sports science support staff. Data Collection: Reflective logs (lead researchers and other trainers), video observations of training sessions, and team meetings. Data Analysis: Systematic data analysis: organizing/subtracting data, familiarizing oneself, coding into first/high level themes, looking for evidence to corroborate claims.	The coaching team made significant progress in their collaboration, learning, and pedagogical practice. Collaboration: Initially a lack of involvement in joint planning, but increased engagement through a drive to reflect and discuss during meetings. Coach Learning & Pedagogical Practice: Identifies the need to change coaching approaches to improve player understanding and decision-making. An initial pedagogical lack of knowledge among trainers was identified, prompting head coaches to educate them on different strategies (e.g., Problem-Based Learning – PBL). The application of a more " <i>player-centred</i> " approach and PBL significantly improves the understanding of the player's game. CAR provides opportunities for coaching teams to develop their motivation, pedagogical knowledge, coaching practice, and reflective abilities. Action research is an effective way to develop expert knowledge and is an ongoing process that trainers should consider.
8.	(Smith et al., 2018)	To examine how leader communication inspires athletes in the context of team sports. In particular, to understand how leaders communicate in an inspiring way, learn from authentic recordings of elite leaders, and provide more detailed information about aspects of communication that affect player perception.	Design: Embedded mixed method design (especially qualitative with initial quantitative data). Participants: 20 men's club standard team sports players (10 rugby, 10 other team sports; Mage = 22.45 years). Stimulus Material: Authentic footage of an elite rugby coach and athlete leader (British and Irish Lions rugby union team, 1997 tour DVD) delivering a speech. Data Collection: Participants watched the clip, identifying moments of inspiration using a 7-point (quantitative) inspiration scale. A follow-up semi-structured interview is conducted, replaying inspiring segments, asking the " <i>why</i> " question. Data Analysis: Thematic content analysis for qualitative data, Mann-Whitney U test for quantitative inspiration scores between groups.	Six key dimensions of inspiring communication content emerge: Stating the challenges and rewards of success; Creating and increasing confidence; Embrace and strengthen underdog status; Showing how the team can be successful; Empowering athletes to take personal responsibility; Creating pride and unity within the team. Effective delivery features include: tone of voice, fluency in speech, use of pauses, repetition, and emphasis, building intensity on key points. Participants respond more positively when leaders promote a sense of group identity (e.g., using " <i>unity</i> ", " <i>chain</i> ", " <i>badge</i> "). It is recommended that someone with the highest inspirational qualities should deliver a speech, regardless of their formal leadership role.

9.	(Campo et al., 2019)	To test the effectiveness of Emotional Intelligence (EI) training interventions in sport to improve EI at trait levels, particularly in participants who were not previously motivated to do so.	Design: Intervention study with experimental group and control group. Participants: 67 players from professional rugby clubs. Professional team (N = 31) as the intervention group, U23 team (N = 36) as the control group (non-random). Data Collection: A trait EI questionnaire (TEIQue, French version) is filled out on pre- and post-tests. Intervention: Four face-to-face sessions over five months, with homework and follow-up procedures. The control group attended a video match analysis session. Data Analysis: MANOVA repeated measurements, with age as a covariate.	EI training is partially successful in improving EI at the trait level, particularly in subscales such as social competence, emotion perception, and emotion management, but not global EI of a nature. Adding age as a covariate reduces the size of the effect of EI training. Age is positively correlated with EI traits. It is possible to increase EI even in participants without pre-existing motivation. The results highlight encouraging developments in EI research.
10.	(Barden et al., 2022)	To assess the barriers and facilitators for coaches in implementing the Activate injury prevention training program in English men's school rugby.	Design: The qualitative study uses a framework approach, with four a priori themes (awareness, motivational determinants, volitional determinants, socio-environmental factors). Participants: The target sample was 10 boys' school rugby coaches from schools across the UK. Data Collection: Semi-structured, one-on-one interviews (50-70 minutes each) conducted through Microsoft TEAMS. Data Analysis: Thematic coding using NVivo, combining code into sub-themes in a priori theme.	Trainers generally have a positive perception of Activate, demonstrating a good knowledge of the effectiveness of the program. However, no trainer implemented Activate as per the original purpose; They highly adapt the delivery to fit their context, often for a variety of sports or by choosing a specific exercise. Barriers identified: Lack of coaches' awareness of poor Activate/dissemination of RFUs, time constraints, lack of player involvement, use of non-rugby-oriented teaching staff. Identified facilitators: Knowledge of Activate effectiveness and injury prevention, granting players autonomy to warm up, RFU resources, staff support. Players are often the agents of program delivery, although dissemination and training resources are directed to coaches. Requiring Activate training as part of a coaching qualification can increase self-awareness and efficacy.
11.	(Sly et al., 2022)	To analyse knowledge and perceptions of injury prevention and IPEP among staff, parents and players in youth rugby union, and to explore facilitators and barriers to IPEP implementation, in order to create tailored implementation strategies.	Design: Cross-sectional online survey. Participants: Community rugby union players aged 14–18, their parents, and staff (coaches, doctors, physiotherapists, S&C staff, team managers) in Australia. The survey was completed by 18 staff, 72 parents, and 56 players. Data Collection: An online survey with sections on demographics, competition logistics/resources, injury/prevention knowledge/perception, and rugby-specific IPEP knowledge/perception. Includes multiple-choice questions and free text. Data Analysis: Descriptive statistics for multiple choice, thematic analysis for free text responses.	Staff, parents and players generally believe that the risk of injury in youth rugby union is high and that injury prevention is important. Concussion and knee ligament injuries are considered 'serious' by most respondents. Strength and conditioning/fitness coaches and physiotherapists are considered the most appropriate people to manage an injury prevention program, followed by coaches. Identified barriers to IPEP completion: Poor attitude or motivation of players and staff, time constraints, lack of program awareness, untimely or poor player attendance. Identified facilitators: Leadership (strong leadership, value-conscious coach), use of role models (peers, professional players), structure and routine (part of a normal routine, incorporated into the schedule, consistency). Highlight the need for practical solutions, education, and consider the role of relevant health staff in facilitating IPEP.

Table 1 summarizes various studies related to sport, particularly rugby and leadership in the context of elite sports teams. The research covers aspects of athlete leadership quality and its impact on team effectiveness (Fransen et al., 2017), the ongoing motivation of elderly amateur rugby players based on the concept of "serious leisure" (Cheng et al., 2016), as well as the influence of social identity on emotions and performance in team sport (Campo et al., n.d.). Another study explored the motivation of Canada's elite women's rugby players in the context of full-contact sport (Kerr, 2015), volunteer support and motivation in women's rugby and the transfer of volunteer activities between contexts (Koutrou & Downward, 2016), as well as coaching collaboration and learning through collaborative action research (Chapron & Morgan, 2020). In addition, the study also discussed the communication of leaders who inspire athletes (Smith et al., 2018), the effectiveness of emotional intelligence training in professional rugby players (Campo et al., 2019), and barriers and facilitators in the implementation of injury prevention programs in school rugby (Barden et al., 2022; Sly et al., 2022). The overall findings highlight the importance of psychological, social and structural aspects in improving performance, continued participation and safety in rugby and elite sports teams.

DISCUSSION

The role of motivation in the performance of rugby athletes

Motivation plays a very important role in determining the performance of rugby athletes. In sports that require strong physical and mental strength such as rugby, motivation is the main factor that affects the level of involvement and consistency of athletes in undergoing training and matches (Durand-Bush et al., 2023). Without sufficient motivation, athletes tend to lose focus and enthusiasm easily, so their performance can decrease (Johnson & Peters, 2014). Intrinsic motivation, which comes from within the athlete himself such as the pleasure and satisfaction of playing rugby, plays a big role in maintaining a long-term commitment (Ajlouni et al., 2023). When an athlete enjoys the process of training and matches, they will naturally be more diligent in training and trying to improve their skills (Behnke et al., 2019). Feelings of satisfaction and pride in personal achievements encourage athletes to continue to develop without having to rely on external factors (Almagro et al., 2020). In addition, extrinsic motivation also provides an additional boost that is no less important (Morris et al., 2022). Awards, social support from family, coaches, and teammates, and expectations for professional achievement can spur athletes to be more active and excited. Mental development through psychological training can strengthen this motivation so that athletes are able to manage stress and improve their performance on the field (Reinebo et al., 2024). With a balanced combination of intrinsic and extrinsic motivation, the performance of rugby athletes becomes more optimal.

The influence of coaches' leadership style on player motivation

The influence of the coach's leadership style on player motivation is significant in shaping team spirit and performance (Keegan et al., 2014). The right leadership style can increase the intrinsic motivation of the player, which is the drive that comes from within to excel and contribute optimally to the team (Xue et al., 2022). In addition, the leadership style also fosters a greater sense of responsibility in players for the overall success of the team, so that they are more passionate and committed in carrying out their respective roles (Fan et al., 2023). Communication by coaches plays an important role in motivating players (Davis et al., 2019). Coaches who are able to provide inspirational communication and support group identity are often more effective at increasing athlete motivation (J. P. Pope et al., 2014). Motivation that comes from inspiration and a sense of community in a team has proven to be stronger and more lasting than motivation that is based solely on formal authority or rules (Scotto di Luzio et al., 2020). As such, coaches need to build positive relationships and encourage players so that they feel valued and involved in the team's process. In addition to communication, the coach's approach that is able to facilitate player-based learning and collaboration between coaches also plays an important role in increasing motivation and understanding of athletes' games

(Larkin et al., 2022). In an environment conducive to learning and collaboration, players feel more involved and have the opportunity to develop their skills independently. This kind of leadership helps players not only be emotionally motivated, but also intellectually in understanding the strategy and objectives of the game, which ultimately improves performance and teamwork.

Social and cultural dimensions in rugby playing motivation

Motivation in playing rugby is greatly influenced by the social and cultural dimensions that surround it (J. Pope & Wilson, 2012). At the community and school level, the desire to demonstrate courage and masculinity identity is one of the main factors that drive individuals to get involved in this sport (Kingsman, 2023). Rugby is often associated with the values of strength, toughness and courage which are considered important in the formation of character and self-image, especially for young men (Paul et al., 2022). In addition, group solidarity also plays a significant role in motivation to play rugby (Chiwaridzo et al., 2019). The sense of community and unity formed within the team provides a strong incentive to actively participate (Bloom et al., 2003). A supportive social environment, such as coaches, teammates, and the surrounding community, creates an atmosphere that fosters passion and loyalty to the sport, leaving players feeling valued and motivated to continue to improve (Simons & Bird, 2023). At the level of elderly amateur players and women, the motivation to play rugby has shifted focus. They are more driven by a sense of belonging to the sports community, friendship, and self-identification with the values and culture of rugby itself. These psychosocial factors confirm that motivation in rugby is not only based on physical or competitive aspects, but also on complex emotional and social needs, which drive long-term participation.

The role of motivation in volunteering and injury prevention

The role of motivation is crucial in supporting volunteer activities, especially for coaching staff and volunteers in rugby sports environments (Neely et al., 2022). This motivation is a key factor in carrying out their roles consistently and dedicatedly. Through strong motivation, they not only help develop players' abilities, but also contribute to the success of safety programs that aim to prevent injuries while competing or practicing. The motivational factors that drive volunteer engagement are very diverse. Some of them are motivated by the expression of personal values, such as a passion to help others and contribute positively to the sports community. In addition, the love for the sport of rugby itself is also a major driver that makes volunteers feel satisfied and continue to participate in various activities. This intrinsic motivation is able to significantly improve the quality and quantity of volunteer involvement. However, challenges such as lack of awareness of the importance of volunteers' roles as well as time constraints are major obstacles that must be overcome (Southby et al., 2019). For this reason, proper training and continuous support are needed so that the coaching staff and volunteers can carry out their duties optimally. With this approach, injury prevention programs and volunteer activities can run more effectively and support the overall development of the sport of rugby.

Interventions and training to improve motivation and performance

Interventions and training designed to improve the motivation and performance of rugby athletes have an important role to play in supporting team performance (Sato et al., 2023). One approach that shows significant potential is emotional intelligence training. By improving athletes' ability to recognize, understand, and manage their own emotions, this training helps players to deal with pressure during games more effectively (Kopp et al., 2021). In addition, the development of the team's social identity is also the main focus in this intervention. When players feel connected and have a strong sense of community within the team, they tend to show higher motivation and a better fighting spirit. A strong social identity creates an emotional bond between team members, which contributes to creating a positive atmosphere on the field. Overall, this training strategy that combines psychological aspects has a real positive impact on the performance of rugby athletes.

A comprehensive approach not only improves the technical and physical aspects but also focuses on the mental and emotional well-being of players. Thus, the development of rugby athletes becomes more holistic and sustainable, resulting in optimal performance in every match.

Practical implications for policy trainers and developers

The findings suggest that coaches need to adopt leadership styles that are both intrinsically and extrinsically motivating, build a team climate of strong solidarity and social support, and pay attention to the diversity of athletes' sociocultural backgrounds. Support in the development of emotional intelligence and effective communication is also key in improving athlete performance and safety. In addition, the development of volunteer training and injury prevention programs that take into account motivations and on-field barriers is critical to the sustainability of rugby more broadly.

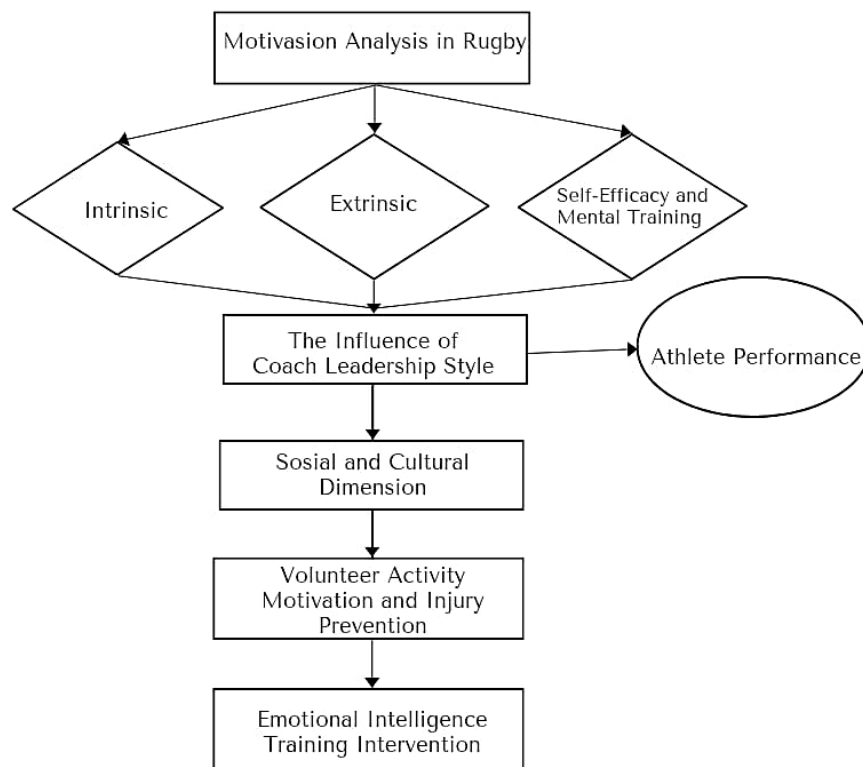


Figure 2. Framework Motivation analysis rugby.

Recommendations for further research

The future research recommendation in this study is to explore more deeply the influence of rugby coaches' transformational and democratic leadership styles on athletes' intrinsic and extrinsic motivations in the context of intensive training and competition, taking into account moderation variables such as sociocultural background and emotional intelligence of players. Research can test the effectiveness of leadership training interventions focused on developing inspirational communication and psychological support to improve ongoing motivation as well as overall team performance. In addition, it is important to examine the role of motivation in stress management and athlete injury prevention, as well as how coaches and volunteer staff can be optimised through motivation-based training to support the safety and sustainability of the sport of rugby. This multidimensional approach will provide a comprehensive overview of the most effective leadership and motivational strategies in the development of rugby athletes at various levels.

CONCLUSION

The conclusion of this study is that motivation, both intrinsic and extrinsic, plays a key role in improving the performance of rugby athletes. The coach's inspirational and supportive leadership style is able to significantly increase player motivation, which has a positive impact on the effectiveness of the team. In addition, social and cultural factors also play an important role in shaping athletes' motivation, especially in terms of identity, solidarity, and a sense of belonging to sports. Motivation is also important for coaching staff and volunteers for the sustainability of the sport development and safety program. Interventions that focus on emotional intelligence training and effective communication can significantly improve athletes' motivation and performance. Therefore, coaches and policy makers are advised to integrate a motivating leadership approach, strengthen a solid social climate, and pay attention to the diversity of athletes' backgrounds to improve performance and safety in rugby.

AUTHOR CONTRIBUTIONS

Nanang Indriarsa: Visualization, investigation. Suryanto Agung Prabowo: Data curation. Anung Priambodo: Conceptualization, data curation. Rizki Satrio Utomo: Formal analysis, data curation. Ainun Zulfikar Rizki: Writing – review. Alvin Afandi: Methodology, writing – review, editing.

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Global map of tennis elbow literature: A bibliometric analysis supported with statistical methods



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ABSTRACT

The study aimed to evaluate global trends by analysing bibliometric data on tennis elbow research indexed in the Web of Science (WOS) and to test the significance of bibliometric trends with statistical methods. The study design followed the BIBLIO checklist protocol to ensure high reporting quality. The WOS database was used to obtain bibliometric data, and 895 research articles meeting the inclusion criteria were included in the study. Bibliometric results were reported with figures, while the statistical significance of the data was assessed using Mann–Kendall trend analysis and Chi-square goodness-of-fit test. Research trends were analysed using Bradford's Law, Lotka's Law, thematic mapping, and factor analysis. There was a statistically significant increase in tennis elbow research over the years ($\tau = 0.83$, $p = .01$). Baker CL had the most studies compared to the other authors ($\chi^2 = 2.74$; $df = 9$; $p = .97$). The most commonly used keywords were "pain," "management," and "tennis elbow." The factor analysis showed a clear divide between treatment methods and epidemiological studies. The results highlighted a research gap in connecting risk factors with disease prevalence and assessing the effectiveness of specific treatments. Also, the thematic map revealed that studies on tennis elbow have primarily focused on pain management, while surgical treatment and clinical trials remain underexplored. In conclusion, tennis elbow has been extensively researched in the literature for 40 years. Although pain management is the focus, many research gaps must be developed. Current findings may be guiding for field professionals and practitioners.

Keywords: Tennis elbow, Lateral humeral epicondylitis, Tendinitis, Elbow injuries, Bibliometric analysis.

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INTRODUCTION

Tennis elbow, also known as lateral epicondylitis, is a condition characterized by pain and inflammation of the tendons that attach to the lateral epicondyle of the humerus. Lateral elbow pain affects 1 to 3% of the population, with peak incidence occurring at 40 to 50 (Bisset et al., 2011). The incidence is higher in athletes, especially overhead-throwing athletes (baseball, track and field, handball, volleyball) and tennis players, who combine forceful and repetitive extension movements (Hassebrock et al., 2019). The prevalence of lateral epicondylitis is seven times higher than medial epicondylitis (Cutts et al., 2020). The right hand has an incidence of 63%, the left one 25%, and both hands are affected in 12% of the population (Sanders et al., 2015). The recurrence rate in the population is 8.5%, and the injury may recur in an average of 19.7 months (Sanders et al., 2015).

The ethology of lateral epicondylitis can be defined as repetitive trauma from overuse (Kroslak & Murrell, 2007). Repetitive extensor carpi radialis brevis muscle eccentric contractions may alter tendon structure and cause a degenerative process to begin (Hofwegen Van et al., 2010). Researchers also argued that other risk factors are microvascular lesions, cutaneous nerve injury, anatomic predispositions, improper technique and equipment, altered loading patterns, and joint biomechanics (Anghel, 2023; Kandemir et al., 2002). This clinical presentation of lateral epicondylitis may vary, and it can lead to cessation of activity in athletes. Functional use of the involved upper extremity can be limited, and usually, gripping activities exacerbate the symptoms. Also, resisted wrist extension, radial deviation, finger extension, and forearm supination can produce pain. Other symptoms include diminished grip strength, elbow stiffness in the morning, limited range of motion secondary to pain, tenderness at the lateral epicondyle, and radiating pain down the forearm. The previous studies reported that radial tunnel compression can accompany lateral epicondylitis in up to 10% of that population (Izzi et al., 2001; Orchard & Kountouris, 2011).

The treatment of tennis elbow can be conservative or surgical. Even if the success rate of nonoperative treatment can be up to 90%, 4 to 11% of the patients ultimately require surgery. For the patients who follow conservative treatment, this includes patient education, physical therapy, medications, acupuncture, braces, and injections (Hofwegen Van et al., 2010; Onu et al., 2021). However, researchers found no evidence that surgical interventions for tennis elbow are more effective than non-surgical interventions (Bateman et al., 2017).

The impact of tennis elbow on athletes' performance may vary based on the intensity of symptoms and the rest period. The return to sports after arthroscopic treatment for lateral epicondylitis reported in the literature varies between 2 to 16 weeks (Dunkow et al., 2004). After arthroscopic surgery, the average return to sports was 8.6 weeks (Oki et al., 2014). Researchers reported that a return to sport was made in 35 days for patients who performed arthroscopic surgery, compared to open surgery patients, who returned to sports in 66 days (Kumar et al., 2015). Some studies reported a local muscle imbalance among forearm muscles (Alizadehkhayat et al., 2007) and global upper limb weakness in recovered tennis elbow (Alizadehkhayat et al., 2009). This indicates an incomplete functional recovery of the patient with lateral epicondylitis and suggests the necessity to follow a global and holistic approach in the treatment of this pathology.

Researchers have recently employed bibliometric analysis to uncover the challenges associated with research on tennis elbow and identify emerging trends within the field (Xu et al., 2023; Zhu et al., 2023). Researchers favour this analytical approach to determine research trends, identify the most cited articles, recognize influential researchers, pinpoint key journals and countries, map collaboration networks, and assess other critical scientific indicators (Donthu et al., 2021). While bibliometric analyses have been

conducted in this research area, existing studies have limitations concerning the bibliometric analysis methodology. The primary limitation is the number of studies included in the analysis. A previous bibliometric analysis examined the 100 most-cited research articles on tennis elbow (Zhu et al., 2023). However, other researchers have argued that the scientific impact cannot be measured solely by citation counts (Vancloy, 2012). Since bibliometric analysis aims to provide a comprehensive overview of a research field (Aria & Cuccurullo, 2017), an analysis based on only 100 articles may not adequately represent the entirety of tennis elbow literature. Another limitation of existing studies is the type of articles included in the analysis. Previous bibliometric analyses also incorporated review articles (Xu et al., 2023; Zhu et al., 2023). However, review articles have been reported to receive three times more citations than the original research articles (Miranda & Garcia-Carpintero, 2018). This discrepancy may compromise the reliability of bibliometric data concerning citation counts and could result in significant studies within the field being overlooked. Additionally, prior studies did not use quotation marks for the keywords identified during the electronic search (Xu et al., 2023; Zhu et al., 2023). Enclosing recorded keywords in quotation marks is essential for enhancing the effectiveness of electronic searches (Bramer et al., 2018). The absence of quotation marks in word combinations may have led to the inclusion of studies not directly related to tennis elbow in the bibliometric analysis. Finally, owing to limitations in the data extraction methods employed in previous studies, researchers have emphasized the need for improved bibliometric analyses of tennis elbow using more precise methodologies (Xu et al., 2023; Zhu et al., 2023).

A bibliometric analysis that addresses the existing limitations can provide a more accurate representation of the research field. More robust interpretations of the study findings can be derived by testing the statistical significance of the obtained bibliometric data and evaluating it using alternative statistical methods. The primary aim of this study was to conduct a bibliometric analysis of research articles on tennis elbow indexed in the Web of Science (WOS). An additional aim was to enhance the study results' reliability by assessing the bibliometric data's accuracy through statistical analyses. The following statement serves as the problem statement for this study: What are the emerging trends in research articles on tennis elbow indexed in the WOS?

MATERIAL AND METHOD

Study design

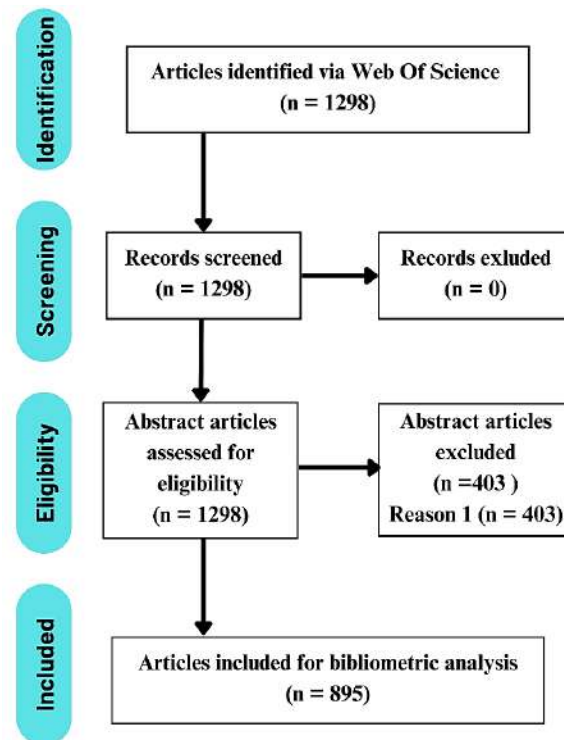
This study employed a quantitative research approach to analyse numerical data. The study protocol was registered in the Open Science Framework (OSF) (DOI:[10.17605/OSF.IO/Y35DE](https://doi.org/10.17605/OSF.IO/Y35DE) accessed August 23, 2024). The study protocol was carried out according to the criteria in the BIBLIO checklist to improve reporting quality (Montazeri et al., 2023). The checklist details are presented in Appendix 1. Additionally, all documents utilized in this study were presented as open access to the OSF (<https://osf.io/y5gke>).

Search strategy

Two independent researchers conducted a literature search using the Web of Science Core Collection (Clarivate Analytics, Toronto, Canada). Medical Subject Headings (MeSH) terms were analysed to identify relevant keywords for the literature search, and expert opinions were considered. The following keyword combinations with Boolean operations were employed to identify studies on tennis elbow: "*Lateral Epicondylitis*" (Title), "*tennis elbow*" (Title), "*Lateral Epicondylitis*" (Title), "*Humeral Epicondylitides*" (Title), and "*Lateral Humeral Epicondylitides*" (Title). (<https://www.webofscience.com/wos/woscc/summary/21ddf5fb-ea61-472f-bdf5960c3c5da50d-fcc6e42a/relevance/1>), accessed August 22, 2024). The researchers reviewed the abstracts and titles of all the studies to confirm their relevance to the research field.

Inclusion and exclusion criteria

The word combination of the study was scanned in the WOS electronic database with only the “Title” criterion, and the aim was to identify the most relevant studies in the research field. Only “Article” was selected as the document type to identify subject trends. There were no restrictions on criteria, such as publication time, publication language, and journal index. Details of the screening results based on the inclusion and exclusion criteria are presented in Figure 1.



Note. Reason 1: Other types of documents that are not original articles (such as reviews, letters to the editor, books).

Figure 1. Study flow diagram for articles included in the bibliometric analysis.

Statistical analysis

The studies were exported as the “*bib.tex*” from the WOS to conduct bibliometric analyses. The certainty of the evidence from the data was reported as a percentage. The statistical frequencies derived from the documents were utilized for bibliometric analyses. Time-based bibliometric data were assessed using Mann–Kendall trend analysis to determine the statistical significance of the results obtained. Changes in bibliometric data over time were reported using tau and *p*-values. Conversely, the Chi-square goodness-of-fit test was employed to assess non-time-based bibliometric data. A *post-hoc* analysis, utilizing the Bonferroni correction, was conducted when statistically significant differences between groups were identified. The results were reported using the chi-square value, degrees of freedom, and *p*-value based on the degree of compliance between the observed frequencies in the bibliometric data and the theoretical or expected frequencies.

In addition to the frequency-based bibliometric analyses conducted in this study, Bradford's law distribution, Lotka's law distribution, thematic analysis, and factor analysis with biplot were employed. Bradford's Law distribution was utilized to illustrate how articles published in the literature on tennis elbow are concentrated in specific journals. In contrast, Lotka's law was applied to interpret the distribution of author productivity in this field. A thematic map was chosen to visually represent the concepts in the research area and the

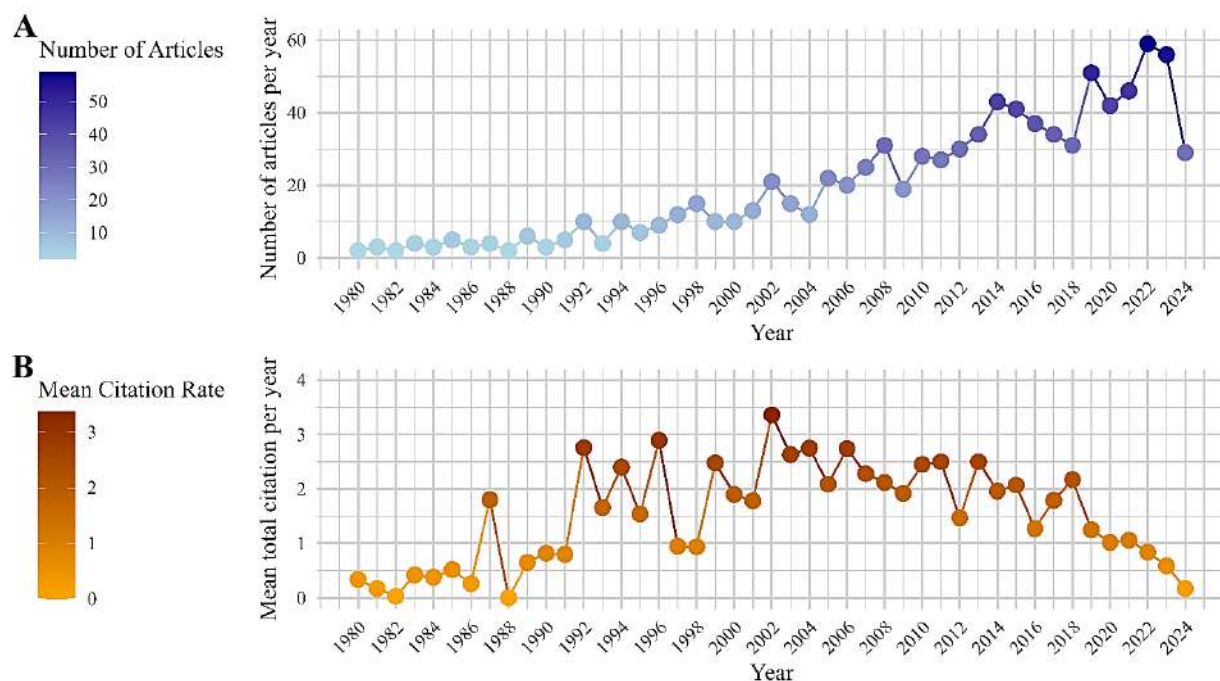
relationships among them, while factor analysis aimed to identify the ideas that differentiated this research area. All statistical analyses were performed using the R software (version 4.1.1, Core Team, Vienna, Austria). The following packages were used to conduct these analyses: {bibliometrix}, {ggplot2}, {dplyr}, {patchwork}, {kendall}, {extrafond}, {tidyverse}, and {scales}.

RESULTS

Scientific productivity results for tennis elbow studies

The literature search indicated that studies on tennis elbow had been indexed in the WOS since 1980. A total of 895 articles were included in this study (Figure 1). The highest number of publications in this research field occurred in 2022, with 59 articles. It was noted that the literature on tennis elbow continued to develop at a rate of 14%. This development was evaluated statistically, revealing a significant upward trend in scientific publications per year ($\tau = 0.83$, $p = .01$). The results demonstrated that this trend has persisted since 1984.

The year with the highest average citation rate for tennis elbow was 2002, with a citation rate of 3.36. A comparison of the yearly citation rates revealed no statistically significant trend in the annual citation rate from 1980 to 2024 ($\tau = 0.18$, $p = .07$). Details regarding scientific productivity are presented in Figure 2.



Note. A: annual number of scientific publications; B: Annual mean total citation rate.

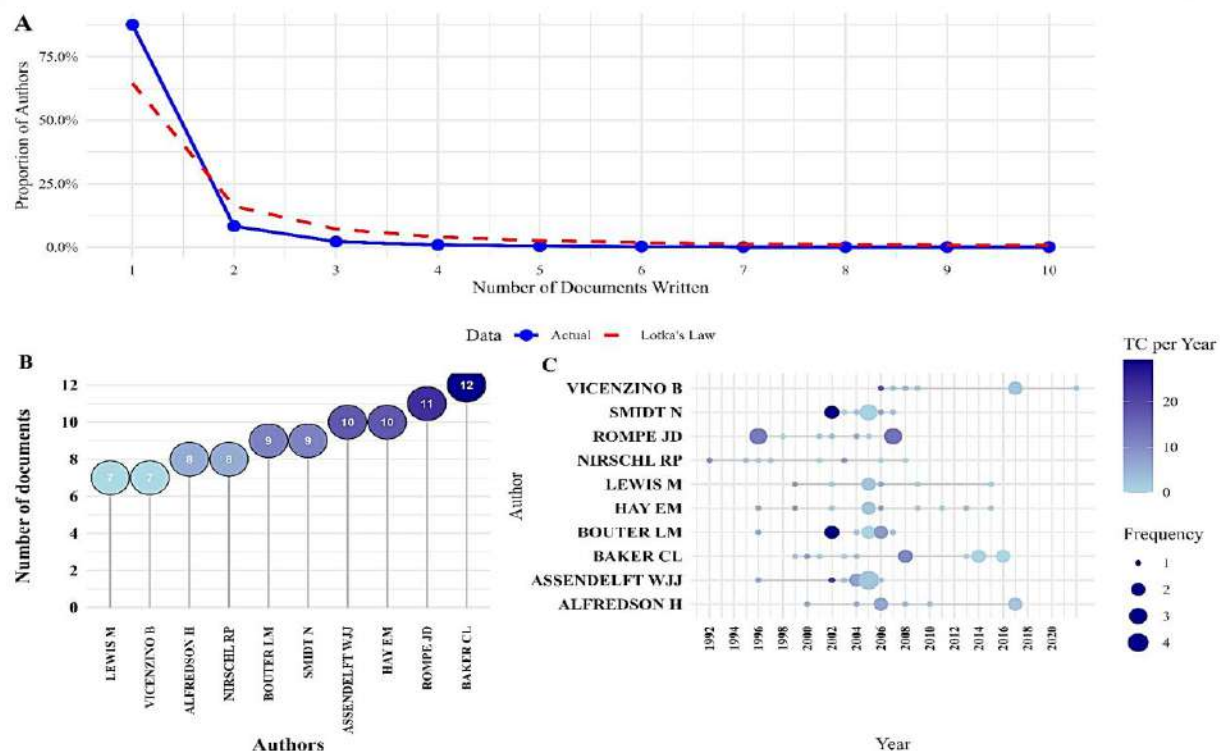
Figure 2. Scientific productivity results for tennis elbow studies.

Results for researchers studying tennis elbow

The distribution of researchers publishing on the subject according to the number of articles was evaluated using Lotka's law (Figure 3a). The results revealed that more than 75% of researchers wrote only one article. The number of researchers decreased as the number of articles written increased, and these results showed that most researchers published a limited number of articles on this subject. Therefore, it is understood that a few researchers have had a dominant effect on the literature.

The obtained dataset determined that 3432 authors were published in the research field, and the number of articles of the ten authors with the most publications was reported. The results showed that Baker CL was the researcher with the most publications on tennis elbow (Figure 3b), but no statistically significant difference was found between the number of articles by the first ten authors ($\chi^2 = 2.74$; $df = 9$; $p = .97$).

When the authors' tendency to research tennis elbows according to the years was evaluated, it was observed that Vicenzino B had conducted research on tennis elbows in recent years (Figure 3c). Although Baker CL last conducted research on tennis elbow in 2016, only Baker CL out of 10 researchers researched tennis elbow with a statistically significant and increasing trend ($\tau = 0.63$, $p = .05$). No statistically significant trend was found in the studies conducted by the other nine researchers over the years ($\tau = -0.11$ to 0.62 , $p = .36$ to 1).



Note. A: Author Productivity Actual vs Lotka's Law. The blue line (Actual) represents the document writing rate of authors with actual data. In contrast, the red dotted line (Lotka's Law) means the document writing rate of authors expected according to Lotka's Law; B: Total number of publications of the top 10 authors who published the most on tennis elbow. Larger and darker bubbles indicate a higher number of document; C: Tendency of the top 10 most published authors to examine tennis elbow by year. The lines on the x-axis represent the years the authors researched the topic. The size and colour of the bubbles indicate the number of citations per year. Larger, darker bubbles indicate higher citation counts.

Figure 3. Results of researchers' scientific productivity.

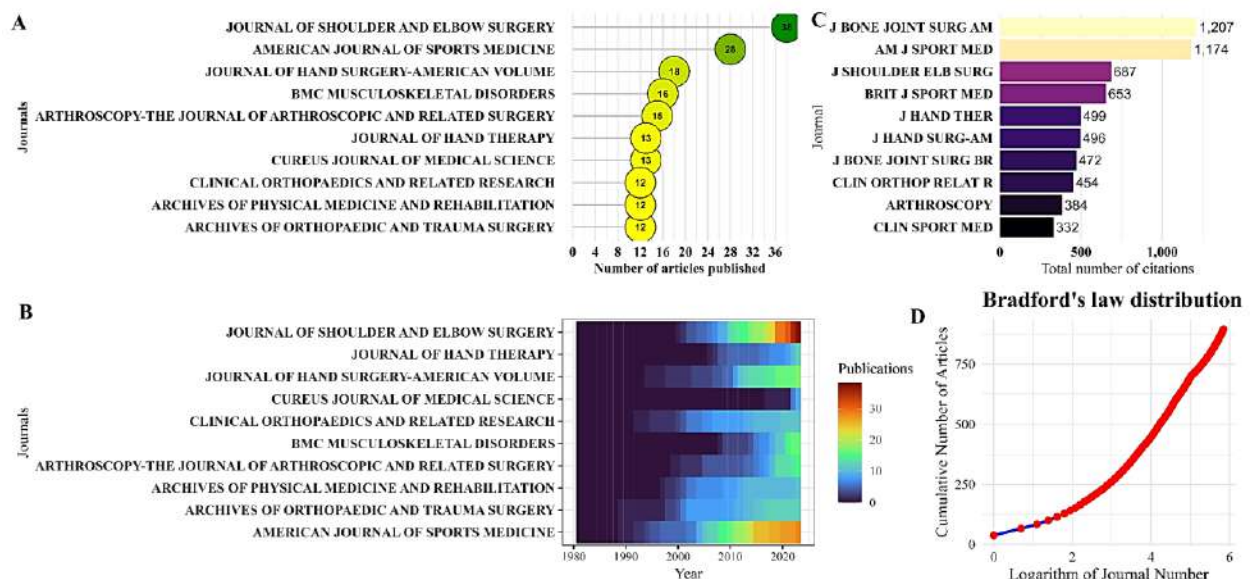
Results for journals accepting studies on tennis elbow

The ten journals that published the most articles on tennis elbow were evaluated, revealing that the Journal of Shoulder and Elbow Surgery exhibited the highest propensity to accept submission (Figure 4a). The results of the chi-square goodness-of-fit test indicated a statistically significant difference in the journals' tendency to accept publications on this topic ($\chi^2 = 37.86$; $df = 9$; $p = .01$). Post-hoc analysis demonstrated that the

Journal of Shoulder and Elbow Surgery had a statistically significant higher acceptance rate for tennis elbow studies than other journals (expected number of articles = 17.7; number of published articles = 38; $p = .01$).

When the journals' tendency to accept publications on tennis elbow was examined by year, it was found that the journals that accepted the most publications since 1980 were the Journal of Shoulder and Elbow Surgery and the American Journal of Sports Medicine (Figure 4b). When these results were compared statistically, no statistically significant tendency was found for the Archives of Orthopaedic and Trauma Surgery ($\tau = 0.08$, $p = .51$) and the Archives of Physical Medicine and Rehabilitation ($\tau = 0.19$, $p = .11$). In contrast, other journals demonstrated a statistically significant and increasing trend in accepting publications on tennis elbow since 1980 ($\tau = 0.96$ to 0.23 , $p = .01$).

When evaluating the total citation counts of the ten journals that published the most articles on tennis elbow, it was found that the journal with the highest number of citations was The Journal of Bone & Joint Surgery, which had 1,207 citations (Figure 4c). Additionally, a statistically significant difference was observed between the total citation counts of the journals ($\chi^2 = 1372.60$; $df = 9$; $p = .01$). Post-hoc analysis revealed that The Journal of Bone & Joint Surgery (expected total citations = 635.8; actual total citations = 1,207; $p = .01$), American Journal of Sports Medicine (expected total citations = 635.8; actual total citations = 1,174; $p = .01$), and Journal of Shoulder and Elbow Surgery (expected total citations = 635.8; actual total citations = 687; $p = .01$) had citation counts significantly higher than expected. Although statistically significant results were found for other journals, their citation counts were lower than anticipated ($p < .05$).



Note. A: Journals that accept the most publications on tennis elbow. Darker bubbles indicate a higher number of articles; B: Number of publications in journals by year. The colour scale shows the number of publications per year. Redder colours represent more publications; C: Most cited journals. The length and colour of the bars vary according to the number of citations. Longer, lighter bars indicate more highly cited journals; D: Bradford's Law distribution. The blue line shows the distribution of journal articles published with the actual data, while the red line shows the expected distribution according to Bradford's Law.

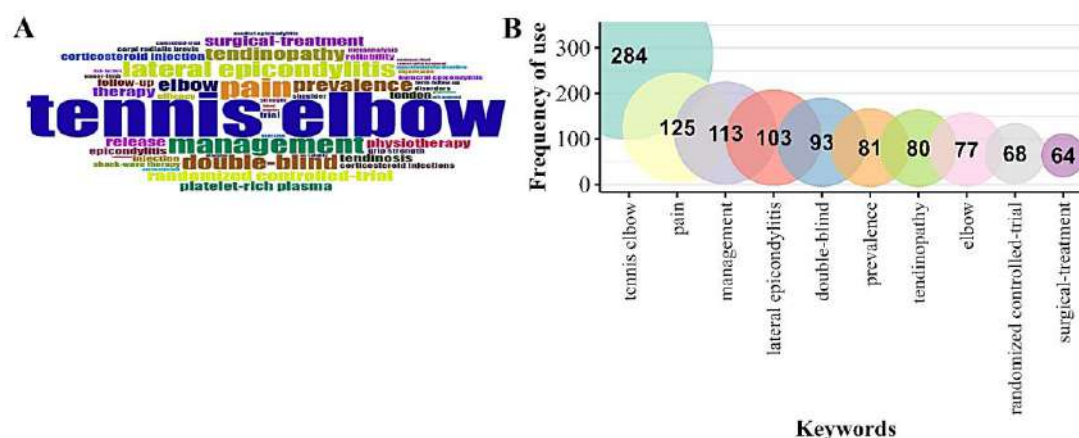
Figure 4. Journal publication trends in tennis elbow studies.

The results for journals accepting studies on tennis elbow were evaluated according to Bradford's law distribution (Figure 4d). The results showed that the cumulative number of articles increased at a specific

rate, with more journals providing fewer articles. Bradford's law revealed that most articles on tennis elbow were published in a relatively small number of journals. Details of the journals accepting studies on tennis elbow are presented in Figure 4.

Results for keywords used in tennis elbow studies

The most preferred keywords in the studies on tennis elbow were tennis elbow, pain, management, and lateral epicondylitis (Figures 5a and 5b). Researchers significantly preferred the tennis elbow keyword compared to other keywords (expected total keyword frequency = 108.8; actual total keyword usage = 284; $p = .01$). The usage frequencies of the keywords pain, management, lateral epicondylitis, and double-blind revealed similar results to the expected usage frequency, and no statistically significant difference was found ($p < .05$). Although a statistically significant difference was found for the keywords surgical treatment, randomized controlled trial, elbow, tendinopathy, and prevalence ($p = .01$), it was understood that these keywords were preferred less than the expected usage frequency. Details regarding the keywords used in tennis elbow studies are presented in Figure 5.



Note. A: Keyword cloud for keywords. More prominent keywords indicate more frequent usage; B: The ten most used keywords by researchers and their frequencies.

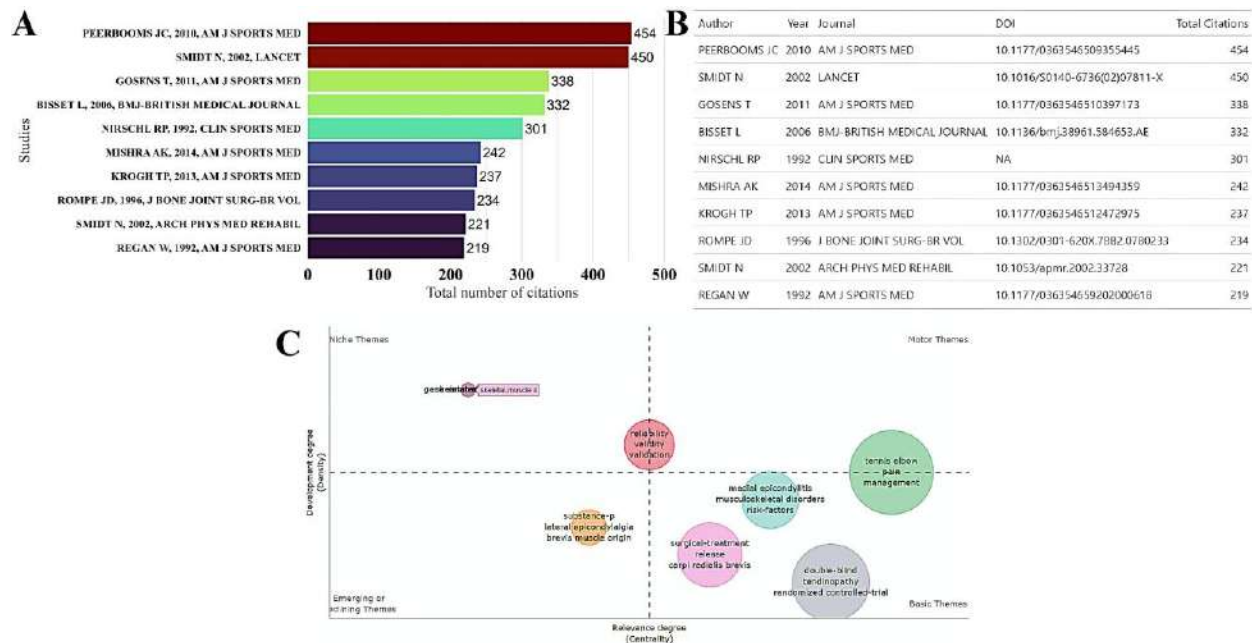
Figure 5. Frequency of keyword usage by researchers.

Results for study trend in tennis elbow studies

Trends in studies on tennis elbow were assessed (Figures 6a and 6b), and four studies (Bisset et al., 2006; Gosens et al., 2011; Peerbooms et al., 2010; Smidt, Van Der Windt, et al., 2002) were found to have a statistically significant number of citations exceeding expectations (expected total citations = 302.8; actual total citations = 332 to 454; $p = .01$). Although statistically significant results were also observed in other studies, the total citation counts were below the expected number per study (expected total citations = 302.8; actual total citations = 219 to 301; $p = .01$).

When the thematic map for tennis elbow was evaluated (Figure 6c), it was evident that research on tennis elbow and pain management was the most developed and extensively studied area within this field. However, surgical treatment and clinical trials are essential to address tennis elbows effectively. In addition, researchers have paid little attention to these topics. Studies examining the impact of skeletal muscle structure on tennis elbow have exhibited low centrality despite being intensively researched. Finally, research topics such as substance-p, lateral epicondylalgia, brevis, and muscle origin also demonstrated low centrality and were included in only a limited number of studies. Consequently, it can be inferred that these themes are either

newly emerging or that researchers have lost interest in them. Details regarding the trends in tennis elbow studies are presented in Figure 6.



Note. A: Most cited studies. Longer bars indicate more citations; B: Information on most cited studies; C: Thematic map of tennis elbow studies. Relevance degree (Centrality) indicates the degree of relevance of the study topics, while development degree (Density) describes the degree of development. The upper right theme (Motor themes) generally represents the field's most important and influential research topics. In contrast, the upper left theme (Niche themes) means the study topics necessary for a particular subfield or research group. The lower right theme (Basic themes) forms the basis of the research field and represents research topics with the potential for further development. The lower left theme (Emerging or Declining Themes) indicates potential changes or trends in the research field.

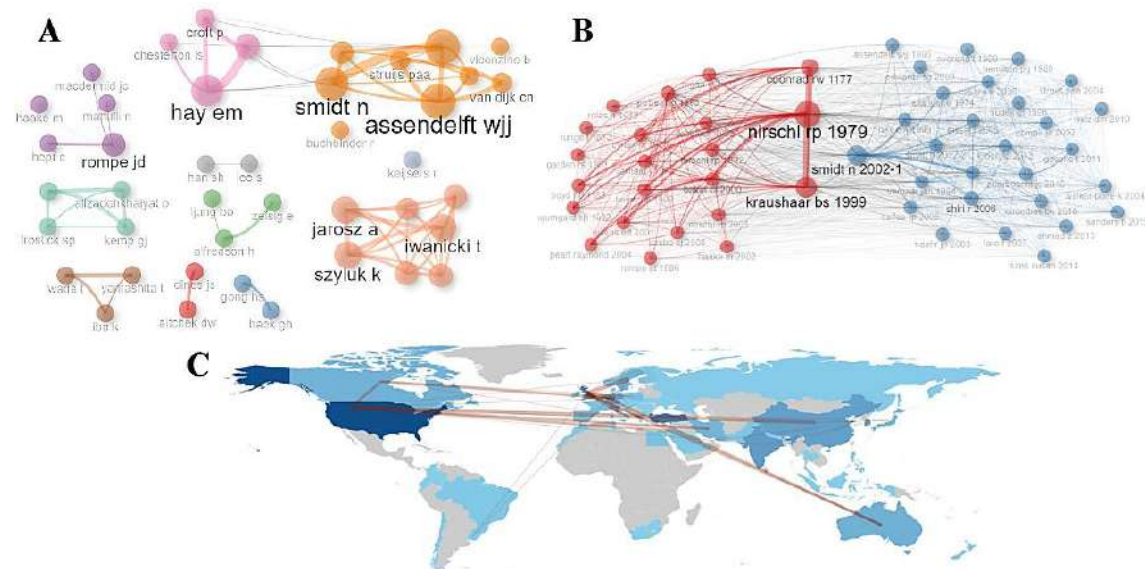
Figure 6. Trends in tennis elbow studies.

Results for the collaboration network in tennis elbow studies

The networks of researchers collaborating on tennis elbow were evaluated, revealing ten groups that exhibited significant collaboration. Among these groups, the most collaborative researchers were Hay EM, Smidt N, and Assendelft WJJ (Figure 7a). Based on the co-citation network results, the studies were categorized into two groups (Figure 7b). Notably, three publications emerged as the most cited within these groups (Kraushaar et al., 1999; Nirschl & Pettrone, 1979; Smidt, Van der Windt, et al., 2002) (Figure 7b). The cross-country collaboration network indicated that the United States had the highest level of collaboration (Figure 7c). Additional details regarding the collaborations on tennis elbow are presented in Figure 7.

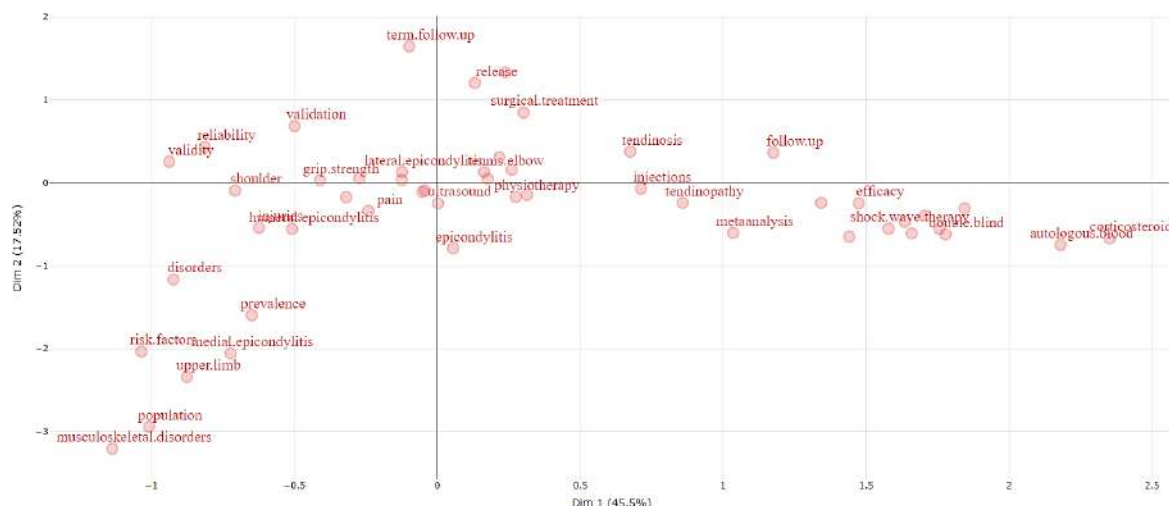
Results for factor analysis in tennis elbow studies

The two-dimensional map of the tennis elbow literature presented in Figure 1 illustrates the field's broad scope and research focus. The first dimension (Dim 1) explains 45.5% of the total variance and reflects a spectrum of the literature that moves from general epidemiology to specific treatment methods. A clear distinction was observed between treatment methods, such as "autologous blood" and "corticosteroid" in the upper right part of the graph, and epidemiological terms, such as "risk factor" and "prevalence" in the lower left part. This finding indicated that studies examining the relationship between risk factors and disease prevalence and the effectiveness of specific treatment methods were insufficient. Details on the factor analysis are presented in Figure 8.



Note. A: Collaboration network between authors. The colour of the node groups defines researchers who collaborate more frequently with each other. The size of the nodes indicates the researchers who collaborates more frequently. The lines explain the collaboration between researchers; B: Co-citation network. The colour of the node groups identifies researchers who are more frequently cited. The size of the nodes indicates the more frequently cited researchers. The lines describe the citation exchange between researchers. C: Collaboration network between countries.

Figure 7. Collaboration network for studies on tennis elbow.



Note. Dim 1 represents the x-axis and Dim 2 represents the y-axis. Dim 1 and 2 percentages represent the proportion of components that make up the data set. A higher percentage is a more critical component for the subject area. Variables that are closer together are described as having a stronger relationship with each other, while variables that are farther apart are defined as less related or independent. Positive values identify variables with a linear relationship with the component in question, while negative values identify variables with a negative relationship with the component in question.

Figure 8. Visualization of study topics on tennis elbow with biplot.

Certainty of evidence of bibliometric data

Articles indexed in the WOS database were used to obtain bibliometric data. No data loss occurred when exporting information on authors, document types, journals, publication years, titles, and citation information. Data loss occurred between 0.67% and 5.92% in the affiliation information of authors and abstracts. While

12.74% of data loss occurred in the information on DOI numbers, data loss for keywords was between 20-30%. Details on data loss are provided in Appendix 2.

DISCUSSION

The aim of this study was to conduct a bibliometric analysis of research articles on tennis elbow indexed in WOS and to evaluate the significance of the results by statistical analysis. The results provided empirical and original evidence for researchers on tennis elbow literature.

The annual number of studies on the tennis elbow has been increasing with fluctuations, while the average number of citations has decreased since 2002. The analysis indicated that these results were statistically significant. Baker CL has conducted research on tennis elbow for 17 years and is the author who has done the most research on the subject. The analysis confirmed the importance of Baker CL for tennis elbow with the statistical significance of the results. The author developed an arthroscopic classification system for lateral epicondylitis and investigated the appropriate arthroscopic treatment methods for patients in different stages. Arthroscopic methods are used more frequently in the treatment of lateral epicondylitis. Arthroscopic debridement and ECRB tendon resection include excision of pathological tissues and partial resection. However, aggressive resection may cause tendon insufficiency and residual pain (Matache et al., 2016). Arthroscopic repair techniques can be used in partial or full-thickness ECRB tendon tears, but inadequate healing may be observed in chronic cases due to poor tendon quality (Burn et al., 2018). Arthroscopic decortication and bone stimulation may increase the fracture risk in the lateral epicondyle and may be limited in chronic cases (Miyazaki et al., 2015). Arthroscopic reconstruction using autologous or allogeneic tendon grafts may cause complications such as donor site morbidity, graft failure, and risk of infection and require a long rehabilitation period (Ruch et al., 2015). Therefore, each patient's condition should be evaluated individually, and the appropriate arthroscopic treatment method should be selected.

Only one of the top 10 journals accepting the most publications on tennis elbow (Cureus Journal of Medical Science) was included in the “*Emerging Sources Citation Index*.” In contrast, the others were included in the “*Science Citation Index*.” These journals focused on traumatology, therapy, and orthopaedics, while the journal accepting the most publications on the subject area was the Journal of Shoulder and Elbow Surgery. This journal focused on medical, surgical, and physical treatment methods for injuries and diseases in the shoulder and elbow region. The analyses confirmed that the Journal of Shoulder and Elbow Surgery accepted the most publications on the subject area with statistical significance levels.

On the other hand, words such as tennis elbow, pain, and management were the most preferred keywords on the subject. The frequent use of these keywords together shows these concepts are closely related. Tennis elbow is a disorder characterized by pain and tenderness on the outer side of the elbow, and pain is the most prominent and disturbing symptom of tennis elbow. An effective treatment/management strategy is essential to controlling pain and improving patients' quality of life. An effective treatment program requires collaboration between different medical disciplines and a multidisciplinary approach. This may explain why treatment/management is often used with pain and tennis elbow. Similar multidisciplinary approaches have been shown to be effective in other upper limb conditions, such as ulnar nerve paralysis (Adina Camelia & Marius, 2021).

This study has also revealed guiding research gaps for researchers who want to research tennis elbow. The thematic map (Figure 6c) showed that the focus of research on tennis elbow revolves around pain management. Most studies have aimed to mitigate pain while addressing physiological, psychological, and

social dimensions (Glowacki, 2015). Various strategies have been explored for pain relief, including physiotherapy, manual therapy, therapeutic exercises, pharmacological interventions, and electrotherapy (Landesa-Piñeiro & Leirós-Rodríguez, 2022). Although surgical treatment and clinical trials are essential for effectively managing tennis elbow, these topics require further investigation. One reason for the limited research on surgical interventions may be that only 2% of patients diagnosed with tennis elbow require surgery (Degen et al., 2018).

Although studies over the last decade have linked tennis elbow to medial epicondylitis and various musculoskeletal disorders, such as carpal tunnel syndrome, De Quervain disease, and rotator cuff tendinosis (Otoshi et al., 2015; Titchener et al., 2013), a comprehensive research strategy is needed to clarify the links between lateral epicondylitis, medial epicondylitis, and other musculoskeletal disorders, this strategy should emphasize the fascial, neurological, and biomechanical factors that contribute to the development of these disorders (Bianco, 2019). A decreasing trend in focus is observed in relation to lateral epicondylalgia, substance P, and the origin of the extensor carpi radialis brevis muscle. Epicondylalgia term was proposed instead of "*lateral epicondylitis*" in 2005. However, experts have not widely accepted this proposal (Waugh, 2005). In addition, the initial focus on the origin of lateral epicondylitis from the extensor carpi radialis brevis muscle has been largely ignored. This concept was central to the early stages of research on lateral epicondylitis. It is now understood that the etiology of lateral epicondylalgia can be tendinogenic, articular, fascial, vascular, or neurogenic (Bales et al., 2007; Shirato et al., 2015). When analysing the study topics on tennis elbow (Figure 8), it is seen that the authors mainly focused on the most frequently encountered keywords, such as pain, lateral epicondylitis, and tennis elbow, and therapeutic methods, such as physiotherapy, ultrasound, and injections.

The literature has confirmed the effectiveness of newer treatment modalities, such as platelet-rich plasma and shock wave therapy (Yao et al., 2020), in managing lateral epicondylitis. However, the positioning of these topics in the lower right quadrant of the graph indicates a deficiency in studies evaluating the effectiveness of these treatments. This scarcity is primarily because these therapies have been widely utilized in clinical practice for approximately a decade, which is insufficient time to establish comprehensive links (Nazaroff et al., 2021). Consequently, the limited number of studies makes it currently unfeasible to develop robust correlational models that involve risk factors, population characteristics, prevalence, and musculoskeletal disorders. These findings suggest potential directions for future research. As previously mentioned, studies investigating the relationships between risk factors, other musculoskeletal disorders, and specific populations should consider emerging trends in the pathophysiological understanding of lateral epicondylitis. This is particularly important for research that emphasizes the roles of the fascial, neurological, and biomechanical systems in identifying sources of pain. Although these connections are present, they are functional, making it challenging to uncover them through evidence-based studies.

This study had some limitations. The first limitation was related to the electronic databases searched. In this study, only the WOS database was searched. In addition, it was understood that the bibliometric findings for keywords had low certainty of evidence. Future studies can conduct research with similar study protocols in different databases. In addition, bibliometric analysis can be limited to current studies to increase the certainty of evidence.

CONCLUSION

This bibliometric analysis comprehensively evaluated the global literature on tennis elbow. The findings indicated a significant upward trend in the volume of publications, particularly in recent years, with pain

management emerging as a central theme. Despite the increasing number of studies, gaps persist in exploring surgical treatments and their efficacy compared to conservative methods. Furthermore, while Baker CL's contributions have notably influenced the field, there was limited collaboration among researchers. Future studies should prioritize a multidisciplinary approach that integrates therapeutic innovations and investigates under-researched areas, such as the relationship between lateral epicondylitis and other musculoskeletal disorders. This analysis can offer valuable insights for guiding future research and clinical practices related to tennis elbow.

AUTHOR CONTRIBUTIONS

Conceptualization: B.A.A., E.A.P., and S.K.; Methodology: S.K. and HŞU; Software: H.Ş.U. and S.K.; Validation: B.A.A. and E.A.P.; Formal analysis: H.Ş.U., and S.K.; Investigation: B.A.A. and S.K.; Resources: E.A.P. and B.A.A.; Writing—original draft preparation: S.K., H.Ş.U., B.A.A., and E.A.P.; Visualization: H.Ş.U.; Supervision: S.K. and E.A.P.; Project administration: S.K., B.A.A. All authors have read and agreed to the published version of the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

DATA AVAILABILITY

Open access to the data is presented available through OSF (<https://osf.io/y5gke/>)

CODE AVAILABILITY

Open access to the codes is presented available through OSF (<https://osf.io/y5gke/>)

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APPENDIX 1. The BIBLIO checklist of the study.

The BIBLIO checklist for reporting the bibliometric reviews of the biomedical literature.

Section/Topic	Item No.	Checklist item	Reported on page No.
Title			
Identification	1	Identify the report as a bibliometric review in the title.	Page 1, Lines 1-2
Issues/topics	2	Indicate the key issues/topics under investigation and coverage of time period.	Page 1, Lines 1-2
Abstract			
Structured summary	3	Structured summary including (as applicable): background, methods, results (key findings) and conclusions.	Page 1, Lines 21-52
Introduction/ Background			
Justification/ Rationale/ Explanation	4	Present review of existing knowledge and epidemiological information.	Pages 2-6, Lines 69-138
Objectives	5	Statement of the objective (s) or question (s).	Page 6, Lines 133-136
Methods			
Search engines (data sources)	6	Describe all information sources (such as electronic databases, contact with study authors, trial registers or other grey literature sources).	Page 7, Lines 151-156
Search strategy	7	Keywords and systematization criteria (date of search, language, type of document) for the search.	Page 7, Lines 147-158
Time period	8	The period that the review covers and the justification.	Page 7, 155-156
Eligibility criteria	9	Describe all inclusion and exclusion criteria; languages; study design, type of publication and time period.	Page 7, Lines 159-166
Data refinement (data selection procedure)	10	Remove the irrelevant articles; inspection to eliminate duplicate and unrelated articles (after evaluation of the title, abstract and content).	Page 7, Lines 159-166, Figure 1
Quality assessment (optional)	11	Assessment of papers by three authors and the use of assessing checklists.	N/A
Data synthesis	12	Describe the methods used for summarizing, handling, synthesis, tabulations or schematic displays. Describe how the data were analysed.	Pages 8, Lines 168-190
Results			
Descriptive findings (statistics)	13	- Provide details of the search and selection process in a flow diagram. - Number of citations retrieved (number of publication, year of publication, type of documents, country of publication, articles with the highest impact, most impactful authors, most impactful articles, authors with the highest production, top journals, top institutions, ...)	Pages 9-14, Figures 1-8
Schematic map and trend	14	Summarize and/or present the schematic maps and trends using an appropriate software to present citations, journals, authors, top journals, time trends, emerging literature, and any relevant indicators (as applicable) [1-5].	Pages 9-14, Figures 1-8
Tabulation and summarizing the findings	15	General recommendation: Studies under consideration could be summarized and organized by different subtitles and different scenarios. Regardless, results need to be presented in separate tables covering each subtitle. The followings are some options that could help to summarize the findings.	Pages 9-14 The results section

		<i>Option 1:</i> - Start the presentation with a historical view [when and who first published on the topic]. - Report on review papers. The result should be listed in a separate table. Also, specify the review type (scoping review, narrative review, systematic review, and meta-analysis). - Summarize the findings according to the study designs and main study types. <i>Option 2:</i> - Start the presentation with a historical view [when and who first published on the topic]. - Report on review papers. The result should be listed in a separate table. Also, indicate the review type (scoping review, narrative review, systematic review, and meta-analysis) should be specified. - Summarize the findings according to outcome measures or populations. For example, see [6]. <i>Option 3:</i> - Start the presentation with a historical view [when and who first published on the topic]. - Report on review papers. The result should be listed in a separate table. Also, specify the review type (scoping review, narrative review, systematic review, and meta-analysis). - Summarize the findings according to concept [7]. <i>Option 4.</i> - Start the presentation with a historical view [when and who first published on the topic]. - Report on review papers. The result should be listed in a separate table, and also specify the review type (scoping review, narrative review, systematic review, and meta-analysis). - Summarize the findings according to different subtitles relevant to the main topic [8].	
Synthesis of findings	16	Synthesize the findings as much as possible, find the gap, and propose a model, hypothesis, etc. (if applicable).	Pages 14-17, Discussion section
Discussion			
Summary of evidence	17	Summarize the main findings. The findings should be presented in more "general" or "accessible" terms.	Pages 14-17, Discussion section
Interpretation	18	Include interpretation consistent with results. Explanations for observed outcomes, similarities, and differences reported would be essential.	Pages 14-17, Discussion section
Strengths and limitations	19	Discuss the strengths and limitations.	Page 17, Lines 395-399
Conclusion(s)	20	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications.	Page 17, Lines 400-410
1. McDougal L, Dehingia N, Cheung WW, Dixit A, Raj A. COVID-19 burden, author affiliation and women's well-being: A bibliometric analysis of COVID-19 related publications including focus on low-and middle-income countries. <i>eClinicalMedicine</i> 2022; 52: 101606. 2. Henstock L, Wong R, Tsuchiya A, Spencer A. Behavioral theories that have influenced the way health state preferences are elicited and interpreted: A bibliometric mapping analysis of the time trade-off method with VOSviewer visualization. <i>Front Health Serv</i> 2022; 2: 848087. 3. Bodea F, Bungau SG, Negru AP, Radu A, Tarce AG, Tit DM, et al. Exploring new therapeutic avenues for ophthalmic disorders: Glaucoma-related molecular docking evaluation and bibliometric analysis for improved management of ocular diseases. <i>Bioengineering</i> 2023; 10(8): 983. 4. Sang XZ, Wang CQ, Chen W, Rong H, Hou LJ. An exhaustive analysis of post-traumatic brain injury dementia using bibliometric methodologies. <i>Front Neurol</i> 2023; 14: 1165059. 5. Ramli MI, Hamzaid NA, Engkasan JP, Usman J. Respiratory muscle training: a bibliometric analysis of 60 years' multidisciplinary journey. <i>Biomed Eng Online</i> 2023; 22(1): 50. 6. Akosman I, Kumar N, Mortenson R, Lans A, De La Garza Ramos R, Eleswarapu A, et al. Racial differences in perioperative complications, readmissions, and mortalities after elective spine surgery in the United States: A systematic review using AI-assisted bibliometric analysis. <i>Glob Spine J</i> 2023; 21925682231186759. 7. Tavousi M, Mohammadi S, Sadighi J, Zarei F, Kerami RM, Rostami R, Montazeri A. Measuring health literacy: A systematic review and bibliometric analysis of instruments from 1993 to 2021. <i>Plos One</i> 2022; 17(7): e0271524. 8. Montazeri A. Health-related quality of life in breast cancer patients: A bibliographic review of the literature from 1974 to 2007. <i>J Exp Clin Cancer Res</i> 2008; 27: 32.			

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Appendix 2. Certainty of evidence of bibliometric data.

Metadata	Description	Missing Counts	Missing %	Status
AU	Author	0	0.00	Excellent
DT	Document Type	0	0.00	Excellent
SO	Journal	0	0.00	Excellent
LA	Language	0	0.00	Excellent
NR	Number of Cited References	0	0.00	Excellent
PY	Publication Year	0	0.00	Excellent
TI	Title	0	0.00	Excellent
TC	Total Citation	0	0.00	Excellent
C1	Affiliation	6	0.67	Good
RP	Corresponding Author	6	0.67	Good
CR	Cited References	37	4.13	Good
AB	Abstract	53	5.92	Good
DI	DOI	114	12.74	Acceptable
ID	Keywords Plus	180	20.11	Poor
DE	Keywords	261	29.16	Poor
WC	Science Categories	895	100.00	Completely missing

Anthropometric and biomechanical factors to predict rowing ergometer performance among collegiate rowers

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ABSTRACT

Purpose: This study examined the relationships between anthropometric and biomechanical variables and 2000 m rowing ergometer performance in novice collegiate rowers. **Methods:** Sixty-six university-level students with basic rowing instruction completed a 2000 m ergometer test. Anthropometric measures (height, mass, wingspan, sitting height, leg length) and biomechanical variables (start output, mean and peak power, distance per stroke) were recorded. **Results:** Significant correlations were found between performance and all anthropometric variables ($p < .01$), with mass ($r = -0.807$) and height ($r = -0.702$) showing the strongest associations. Peak output watts ($r = -0.705$) also correlated strongly with performance. **Conclusion:** Anthropometric and biomechanical variables are significant predictors of 2000 m ergometer performance even in novice rowers, supporting their use for early talent identification and training guidance.

Keywords: Biomechanics, Rowing ergometer, Anthropometric factors, Power output, Stroke length, Performance analysis.

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INTRODUCTION

Rowing is widely recognized as one of the most physically and technically demanding sport disciplines. It is a predominant endurance sport in which muscles of the whole body are used, involving coordinated efforts from the legs, arms, glutes, back, abdominals, pectorals, and shoulders to cover a certain distance (Penichet-Tomás and Pueo, 2017). Steinacker (1993) states that 70% of all of muscle mass is activated in a rowing cycle. But all muscles do not contribute equally to power production (Baudouin and Hawkins, 2002). Telmo (2016) indicates that 46% of the power is provided by the legs, 32% by the trunk and 22% by the arms and Kornecki and Jaszczak (2010), concluded that hip and knee extensors along with shoulder girdle flexors and extensors were those most involved in the production of power during the stroke. Furthermore, since nearly all muscles groups are used in the rowing stroke, a greater range of motion, particularly during the drive, allows for increased muscle recruitment. By optimizing body compression at the catch position, rowers can engage more muscle mass and generate greater force, thereby enhancing the effectiveness of each stroke and improving overall performance. (Akça, 2014; Mikulik, 2009; Yoshiga and Higuchi, 2003). For this reason, some authors have looked for relationships between anthropometric characteristics and performance (Sánchez-Sixto and Floria, 2017).

Bourgois et al. (2000) performed anthropometric measurements on 383 rowers aged 15 to 18 years from 41 different countries who had participated in the World Rowing Championship. Their results showed that height, wingspan and muscle mass were directly related to performance. In a study with rowers of the Croatian national team, Mikulic (2009) found that fat-free mass was the most important anthropometric parameter with a correlation coefficient of 0.767 ($p < .001$) with performance in a 6000 m rowing test. Weight ($r = 0.693$; $p < .001$) and with wingspan ($r = 0.505$; $p < .05$) also showed significant correlations. Penichet-Tomás and Pueo (2017) obtained similar results with 22 elite Spanish rowers using a 2000m rower test: fat-free mass ($r = 0.973$; $p < .001$), height ($r = 0.873$; $p < .001$), mass ($r = 0.894$; $p < .001$) and fat mass ($r = -0.705$; $p < .001$). At a lower performance level, but still with high-level rowers and using a 2000m test, Akça (2014), found correlations in the same direction as those cited above: fat-free mass ($r = 0.822$; $p < .001$), mass ($r = -0.812$, $p < .001$), height ($r = -0.801$; $p < .001$), wingspan ($r = 0.715$; $p < .001$), length of legs ($r = 0.703$; $p < .001$) and sitting height ($r = 0.687$; $p < .001$). Among the limited studies involving novice rowers, Podstawski et al. (2014) investigated 196 physically inactive Polish girls aged between 19 and 23 who had been instructed in rowing techniques in physical education classes. Unlike elite or sub-elite rowers, they found no significant correlation with muscle mass, but they found correlation with height, mass and arm spam.

Focusing on the relationship between power output during the stroke and stroke rate, Muniesa et al. (2011) reported that, in the central section of the rowing competitions, the stroke rate is usually between 34 and 40 strokes per minute, and that there is a linear relationship between power and stroke rate. This contribution is confirmed by Telmo (2016) who explains that the power per stroke increases by 12% when stroke rate rises from 20 to 35 strokes per minute. Therefore, at a higher stroke rate is associated with greater power output per stroke, which in turn contributes to improved overall performance. (Holt et al., 2022).

Finally, regarding the relationship between start strategy and performance, Anderson (2011) compared a fast start versus a continuous start with performance in two tests that lasted less than four minutes. The rowers who had done the fast start finished the test with a 4% advantage. Holt et al. (2021) investigates boat acceleration metrics and their relationship to rowing performance, using quantitative biomechanical data to determine how acceleration at different stroke phases (including the start) correlates with race outcomes. While the study doesn't focus exclusively on the start phase of a race, its findings are relevant. The start involves rapid, powerful strokes to quickly accelerate the boat. The identified acceleration patterns during the

drive and recovery phases can influence the effectiveness of these initial strokes. Therefore, optimizing these acceleration metrics during regular rowing can enhance performance during the critical start phase. Despite the research of Anderson (2011) and Holt et al. (2021) no studies have been published with beginner or intermediate level rowers.

Although numerous studies have examined anthropometric and biomechanical predictors of rowing performance, most focus on elite athletes. Limited research exists on novice or collegiate populations. Understanding these predictors at early stages can inform talent identification and training strategies.

MATERIALS AND METHODS

Participants

A total of 66 male sports science students participated voluntarily in this study (age: 20.65 ± 3.96 years). All participants provided informed consent and were recruited from sports science courses and had received basic ergometer instruction. Anthropometric variables were measured and are presented in Table 1 (Penichet-Tomás, 2016).

Table 1. Mean and standard deviation (SD) of anthropometric variables.

Anthropometric parameter	Mean $\pm$ SD
Height (m)	1.76 ± 0.07
Body mass (kg)	71.77 ± 7.43
Wingspan (m)	1.78 ± 0.08
Sitting height (m)	1.36 ± 0.03
Trunk length (m)	0.92 ± 0.03
Leg length (m)	0.84 ± 0.05

Procedure

Performance was analysed by a 2000 m rowing test (Smith and Hopkins, 2012), using a Concept II model D row ergometers (Lawton et al., 2012) with PM5 monitor, connected to the ErgData application via Bluetooth on the mobile phone and digital tablet. This instrument allowed measuring two power variables (mean and peak output power) and three kinematics (start distance, distance per stroke and mean pace during the test).

Before the 2000m rowing test, participants performed a standard warm-up consisting in: 1 minute rowing with only the arms, 1 minute incorporating the trunk (trunk-arms), 1 minute including the legs but without doing the full stroke length and 7 minutes of full rowing length at 18-20 strokes per minute (at minute 6 from the start, there was an increase of 8 kicks at 28 strokes per minute and at minute 8 another increase of 10 strokes at 30 strokes per minute).

Statistical analysis

Statistical analyses were performed by the Package Social Sciences (SPSS) version 26. First, descriptive statistics were extracted for all variables, and a normality test was carried out. After checking normality and homoscedasticity parametric (Pearson) correlations were done with a 95% ($p < .05$) significance level. Later, lineal regression equations were obtained using those anthropometric variables that had a correlation value of $r > 0.6$.

RESULTS

Kinematic descriptive statistics are presented in Table 2 and its correlation with performance is presented in Table 3. As can be seen, except for the mean pace during the test ($p > .05$) all they present statistically significant correlations, highlighting the peak output watts ($r = -0.705$, $p < .01$).

Table 2. Kinematic descriptive statistics and correlations with performance.

Variable	Mean $\pm$ SD	Range
Mean output watts (W)	217.05 $\pm$ 33.44	156-497
Peak output watts (W)	408.12 $\pm$ 70.15	218-610
Start distance (m)	36.1 $\pm$ 8.43	22.9-58.7
Mean distance per stroke (m)	9.28 $\pm$ 0.98	6-11.3
Mean pace during the test (strokes/min)	28.35 $\pm$ 2.89	23-36

Table 3. Correlation between biomechanical variables and performance.

Variable	r	p
Mean output watts (W)	-0.520	<.01
Peak output watts (W)	-0.705	<.01
Start distance (m)	-0.488	<.01
Mean distance per stroke (m)	-0.497	<.01
Mean pace during the test (strokes/min)	-0.186	.138

All anthropometric variables present significant negative correlations with performance as can be seen in Table 4. Among all of them, the correlation between mass ($r = -0.807$, $p < .01$) and height ($r = -0.702$, $p < .01$) with performance stands out. Negative correlations indicate that higher values of anthropometric measures were associated with faster 2000 m times.

Table 4. Correlations between anthropometric variables and performance.

Anthropometric parameter	r	p
Height (m)	-0.702	<.01
Mass (kg)	-0.807	<.01
Wingspan (m)	-0.682	<.01
Sitting height (m)	-0.550	<.01
Trunk length (m)	-0.547	<.01
Leg length (m)	-0.623	<.01

Table 5. Linear regression equations.

Variable	Equation	R ²	SEE
Height (m)	$y = 938.666 + (-2.650 \cdot x)$	0.49	17.84
Mass (kg)	$y = 664.529 + (-2.684 \cdot x)$	0.64	14.97
Wingspan (m)	$y = 866.955 + (-2.219 \cdot x)$	0.46	18.33
Leg length (m)	$y = 754.723 + (-3.347 \cdot x)$	0.39	19.6
Multiple equation considering these variables	$y = 966.218 + (-308 \text{ height}) + (-2.545 \text{ mass}) + (-1.436 \text{ wingspan}) + (-0.022 \text{ leg length})$	0.809	18.76

Note. R²: determination coefficient; SEE: standard error of the estimate.

Linear regression equations

Using anthropometric variables with correlations greater than 0.6, the linear regression equations presented in Table 5 were calculated.

DISCUSSION

There are several papers that confirm the importance of anthropometric factors in performance in the sport of rowing (Akça, 2014; Mikulic, 2009; Yoshiga and Higuchi, 2003; Penichet-Tomás and Pueo, 2017; Podstawski et al. 2014) but almost all studies focus on experienced (high-level) rowers. Therefore, the aim of this study was to check whether these anthropometric parameters influenced the performance of beginner rowers.

Results showed in Table 2 indicate the associations between performance and the anthropometric parameters analysed. Highlights the great correlation obtained with body mass ($r = -0.807$; $p < .01$) which coincides with the results obtained by Akça (2014), Bourdin et al. (2017), Mikulik (2009), Penichet-Tomás and Pueo (2017) and Secher (1983). In contrast, the results of Podstawski et al., (2014), with a sample of sedentary high school students did not show this level of correlation. This highlights the importance of muscle mass in this sport as explained by Cosgrove et al., (1999), who indicate that a high value of muscle mass is one of the most important predictors of rowing performance in both men and women.

Height also showed a high correlation with performance ($r = -0.702$; $p < .01$). These results agree with those found in the literature in a whole range of different samples: Bourdin et al., (2017) with rowers of international level, Penichet-Tomás and Pueo (2017) with experienced rowers, Akça (2014) with university rowers, and Riechaman et al., (2002) with rowers from a rowing meter championship. Although correlation does not imply causation, the consistency of this result across multiple studies suggests that height may provide a performance advantage in rowing. This relationship can also be seen in the results of top-level competitions, for example, at the 2024 Paris Olympic Games, the medallists for the single sculls event were over 2m tall for men and 1.80m tall for women. The effect of height on performance can be justified on the one hand by the fact that rowing uses the muscles of the whole body (legs, trunk and arms) and, therefore, a larger body size implies more muscles to perform the stroke. On the other hand, because a greater height allows the rower to perform a longer kick and therefore cover more meters in each kick (Huang, 2007).

Leg length ($r = -0.623$; $p < .01$) and wingspan ($r = -0.682$; $p < .01$) showed a medium-to-high correlation with performance. These results agree with those found by Akça (2014), Mikulik (2009) and Penichet-Tomás (2016). Leg action plays a critical role during the initial part of the drive phase, particularly during leg extension. Therefore, greater leg length implies a larger muscular contribution and allows the rower to achieve a longer stroke length. As a result, rowers with longer legs may require fewer strokes to cover the same distance compared to those with shorter legs. (Podstawski et al., 2014; Sebastia-Amat et al., 2020).

Sitting height ($r = -0.550$; $p < .01$) and trunk length ($r = -0.547$; $p < .01$), showed a medium intensity correlation with performance which contrasts with the correlation obtained by Penichet-Tomás (2016). This discrepancy could be explained by the difference in technical level in the samples used, beginners vs international level. It is likely that the advanced technique of high-level rowers enables them to more effectively engage their trunk muscles during the rowing stroke.

Focusing on start variables (average watts, peak watts and distance travelled) results show that peak watts obtained the greatest correlation ($r = -0.705$; $p < .01$), followed by average watts ($r = -0.520$; $p < .10$) and

start distance ($r = -0.488$; $p < .01$). These results agree with those presented by Mäestu et al., (2005) who indicated the importance of a powerful and fast start in rowing tests. Nevertheless, these correlations are not too high, which may be because the duration of the test was more than four minutes, and as Anderson (2011) indicates fast starts are important when doing distances that last less than 4 minutes. Regarding the average distance per stroke, results are like those of Muniesa et al., (2011) who indicate that the greater the distance per stroke, the better the performance because fewer strokes are needed to finish a regatta. However, the intensity of this correlation is not too high ($r = -0.497$; $p < .01$). No significant correlations ($p > .05$) were obtained between stroke rate and performance unlike the results presented by Muniesa et al., (2011) who indicated the linear relationship between stroke rate and performance if the rate does not exceed 40 strokes/minute. The absence of a significant correlation may be attributed to the participants' limited experience with the rowing ergometer, potentially preventing them from maintaining a high stroke rate without compromising technique. Coordinating proper rowing mechanics becomes more challenging at higher stroke frequencies compared to slower ones. Additionally, sustaining a faster pace requires a more developed anaerobic energy system, which likely demands a higher level of training than what novice rowers possess.

By integrating all the results, regression equations have been obtained. These equations may be useful for coaches who want to predict the performance of rowers in amateur categories, without the need to perform a maximum test over 2000 m. Similar to Akça (2014) who establishes equations to predict performance in the 2000 m test, one based on strength tests, another on anthropometric parameters, another on anaerobic tests and a final one that combines all variables.

These findings suggest coaches working with novice rowers can use simple anthropometric assessments to identify potential performance advantages early in training programs.

Although rowing ergometer tests are widely validated in the scientific literature, it is not the natural condition in which canoeing is practiced, so to have greater ecological validity, in future studies it would be desirable to use tests carried out in canoes.

CONCLUSION

This study confirms that anthropometric and kinematic variables are significantly associated with rowing ergometer performance in novice university-level rowers. Greater height, body mass, wingspan, sitting height, and leg length were all correlated with improved performance, suggesting that anthropometric characteristics play a key role even at early stages of rowing development. Among the kinematic variables, peak power output during the start phase showed the strongest relationship with overall performance, highlighting the importance of explosive strength in initial acceleration. In contrast, stroke rate did not correlate significantly with performance, possibly due to the participants' limited technical proficiency and lack of anaerobic conditioning, which may hinder their ability to sustain high stroke frequencies without compromising form. These findings underscore the value of considering both morphological and biomechanical factors in the early identification and training of rowing talent. Future research should examine longitudinal changes in these predictors as rowers advance in training and competition.

AUTHOR CONTRIBUTIONS

Ainoa Santana-Micó: literature review, study design, data collection, data interpretation. Enrique Moreno-Mañas: writing, reviewing/editing a draft of the manuscript, literature review. Salvador Llana-Belloch: study

design, research concept, data analysis, supervision. Alfonso Penichet-Tomas: conceptualization, methodology, data interpretation, statistical analyses.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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Relationship between hip rotational range of motion and isokinetic lower limb strength in elite male alpine skiers

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ABSTRACT

This study aims to clarify the intrinsic relationship between the hip joint range of motion and the isokinetic strength of the hip and knee joints among outstanding male alpine skiers. Twenty-one national-level male alpine skiers were selected for this study. The internal and external rotations of the hip joint in prone and weighted positions were evaluated, along with the total range of motion. The maximum torque, peak power, and other hip and knee joint flexion and extension indicators were measured at angular velocities of 60°/sec and 180°/sec. The results of this study show: (1) There is a negative correlation between the hip joint rotation range in prone and weighted positions and the hip extension and flexion indices in the 60°/sec test; (2) The external rotation angle of the hip joint in the weighted position has a positive correlation with the explosive power of the hip and knee joints in the 180°/sec test; (3) The internal rotation range of the hip joint measured in the prone position has a negative correlation with the total work of hip extension and flexion at 180°/sec and 60°/sec. The results of this study indicate that when evaluating the athletic qualities of alpine skiers, the angular velocity differences between the hip joint range of motion and lower limb muscle strength must be taken into consideration. The range of external rotation angle of the hip joint in the weighted position can be used as an important indicator for evaluating the explosive power of the hip and knee joints. In addition, during training, priority should be given to the dynamic balance of hip joint flexibility and stability.

Keywords: Biomechanics, Alpine skiing, Hip joint range of motion, Lower limb isokinetic muscle strength, Correlation analysis.

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INTRODUCTION

Robust lower body strength is essential for the performance and efficacy of alpine skiers, as the specific technical manoeuvres in this sport predominantly depend on the control and power exertion of the lower body musculature. During turns, athletes must employ hip and knee flexion/extension and adduction/abduction to regulate the angle of the skis and alter direction. The swift contraction of the quadriceps, hamstrings, and gluteal muscles directly influences the fluidity of the turn and the capacity to sustain speed (Hébert-Losier et al., 2014). In challenging snow conditions, lower limb muscle strength is essential for executing precise manoeuvres like propulsion and swift directional shifts. Insufficient strength might result in movement distortion and rhythm disruption, ultimately affecting competition outcomes (Turnbull et al., 2009).

All joints in the human body exhibit varying degrees of flexibility and stability. The technical manoeuvres in alpine skiing underscore the significance of hip joint mobility in this discipline. The hip joint, a ball-and-socket joint, possesses an anatomical configuration that renders it the most flexible joint in the lower limbs, allowing for six degrees of freedom of movement. The range of motion in hip flexion, extension, adduction, abduction, and rotation directly influences the starting length and angle of force generation of core muscle groups, including the quadriceps, gluteus maximus, and hamstrings. Consequently, the mobility of the hip joint and the strength of the lower limb muscles are intricately connected. In alpine skiing, athletes possessing excellent hip joint mobility provide a robust basis for effectively utilizing their lower body strength, while substantial lower body strength contributes to joint stability during full range of motion activities.

Prior research has predominantly concentrated on the correlation between range of motion (ROM) and muscular strength output in isolated joints, overlooking the distinct responses of lower limb multi-joint coordination systems at varying velocities (Baumgart et al., 2021). Moreover, whereas current research has thoroughly investigated the relationship between hip flexion/extension range of motion and lower limb strength, limited studies have addressed the correlation between hip internal rotation range of motion and isometric lower limb strength (Donno et al., 2025; Heinrich et al., 2022). Recent biomechanical studies indicate that the hip joint, as the central component of the lower limb kinetic chain, transmits directional changes in its range of motion through the myofascial chain to distal joints, thereby affecting the efficiency of knee extensor explosive force output (Malfait et al., 2016). The existing literature does not clarify the relationship between hip joint range of motion measurement methods in various positions and isometric muscle strength in the hip and knee joints of the lower limbs. This study utilized the weight-bearing and prone positions to assess hip joint range of motion (ROM). The measurement in the prone position is increasingly utilized in clinical assessments (Takeda & Furukawa, 2022). The assessment of hip joint range of motion in a weight-bearing position more accurately reflects the movement patterns of the hip joint during human activity than assessments conducted in other positions. The assessment of isokinetic strength was conducted at varying angular velocities (60°/s and 180°/s) for the hip and knee joints, demonstrating the intrinsic relationship between hip rotational range of motion and the isokinetic strength of both the hip and knee joints. This offers theoretical justification for the optimization of training strategies and the improvement of competitive performance in alpine skiing athletes.

MATERIALS AND METHODS

Subject of study

This research involved the recruitment of 21 male athletes from the national first-level alpine skiing team as subjects. Table 1 presents their comprehensive basic information. Inclusion criteria: Individuals aged 18 to 25 years who have completed over five years of professional training and hold an athlete grade certificate.

Exclusion criteria include: (1) lower limb orthopaedic diseases and soft tissue injuries that have not healed within the last six months; (2) inability to cooperate in the completion of the experimental process.

Table 1. Basic information of subjects.

Age	Height	Weight	Years of training
20.8 ± 1.18	177.2 ± 5.00	73.3 ± 18.54	5.05 ± 1.24

Test process

ROM measurement

To maintain the accuracy of experimental measurements, all range of motion assessments for participants were performed by the same certified physical therapist. Participants were positioned in prone and weight-bearing orientations during measurement, with the range of motion for hip internal rotation, external rotation, and total rotation documented for each position. The equipment utilized included an iPhone 13 smartphone (iOS 17.3), an XW-W01 smartphone mount, a physical therapy bed, and the Bubble Level and Clinometer smartphone application (Whyte et al., 2021). This application has been utilized in various studies to assess lower limb joint range of motion, with established reliability and validity for research purposes (E. Miley et al., 2019; E. N. Miley et al., 2022; Whyte et al., 2021).

In the prone position, the subject lies on the treatment bed with the pelvis secured by a restraint strap to inhibit rotation. The knee joint of the test leg is flexed at 90°, whereas the non-test leg remains extended and flat on the bed (Charlton et al., 2015). The examiner positions the smartphone at the tibial tubercle, calibrates it to the neutral position of the hip joint utilizing the Clinometer software, stabilizes the pelvis with one hand, and secures the ankle with the other hand. The test leg undergoes passive internal and external rotation around the hip joint axis until it attains its end-range resistance position. The assistant measures the angle difference between the initial and final positions to determine the range of motion, repeating the procedure three times in each direction and calculating the average value.

The subject adopts a half-kneeling position during the measurement of weight-bearing positions. The test leg is flexed at the knee to 90° and supports at least 80% of body weight, whereas the contralateral leg supports less than 20% of body weight and is positioned on a weighing scale for measurement purposes. The subject ensures trunk stability by grasping a chair with both hands (Aefsky et al., 2016). The therapist positions the pelvis horizontally, ensuring alignment of the sagittal plane of the test leg. The subject actively rotates the hip joint both internally and externally to its maximum range, while maintaining a neutral ankle position and avoiding trunk compensation. The therapist observes and documents the maximum rotation angle for each of the three repetitions, calculating the average value thereafter.

Isokinetic muscle strength test

This research employed a multi-joint isokinetic muscle strength testing system (CON-TREX-MJ, PHYSIOMED, Germany), utilizing angular velocities of 60°/s and 180°/s to perform flexion-extension assessments on the hip and knee joints of the subjects. Before testing, the calibration of the equipment was confirmed, and the participants' body positions were adjusted to ensure alignment of the joint axes with the equipment axes, with limbs immobilized to prevent compensation. Participants initially executed three sets of maximum effort flexion and extension movements at a velocity of 60°/s, with rest intervals of 30 to 60 seconds between sets. Following a 2-minute rest interval, the test was conducted again at 180°/s, with three further sets performed. The system recorded metrics including maximum torque, peak power, average power, and total work automatically. Data were systematically organized and stored subsequent to the test.

Statistical methods

The research employed SPSS 27.0 software for statistical analysis. Descriptive statistics were employed to analyse basic information regarding the study subjects, including age, height, weight, and years of training, through frequency analysis. Continuous variables were presented as mean $\pm$ standard deviation (Mean $\pm$ SD). Correlation Analysis: Data conforming to the criteria for normal distribution were subjected to Pearson correlation analysis, represented as ($\bar{x} \pm s$). Spearman rank correlation analysis was employed for data that did not satisfy the criteria for normal distribution. In all analyses, a p -value of less than .05 was deemed statistically significant.

RESULTS

Rapid angular velocity (180°/s)

The constant velocity 180°/s test showed that Prone-HTR was highly significantly positively correlated with PP-KE ($r = 0.374, p < .01$), MP-KE ($r = 0.337, p < .01$), and TW-KE ($r = 0.354, p < .01$). Prone-HIR showed significant negative correlations with TW-HE and TW-HF ($r = -0.346, p < .01$; $r = -0.347, p < .01$) (Figure 1A).

WB-HER showed significant positive correlations with MP-K ($r = 0.381, p < .05$), TW-K ($r = 0.392, p < .05$), MP-H ($r = 0.425, p < .01$), and TW-H ($r = 0.477, p < .01$) (Figure 1B). WB-HT showed a strong positive correlation with TW-HF ($r = 0.432, p < .01$).

Slow angular velocity (60°/s)

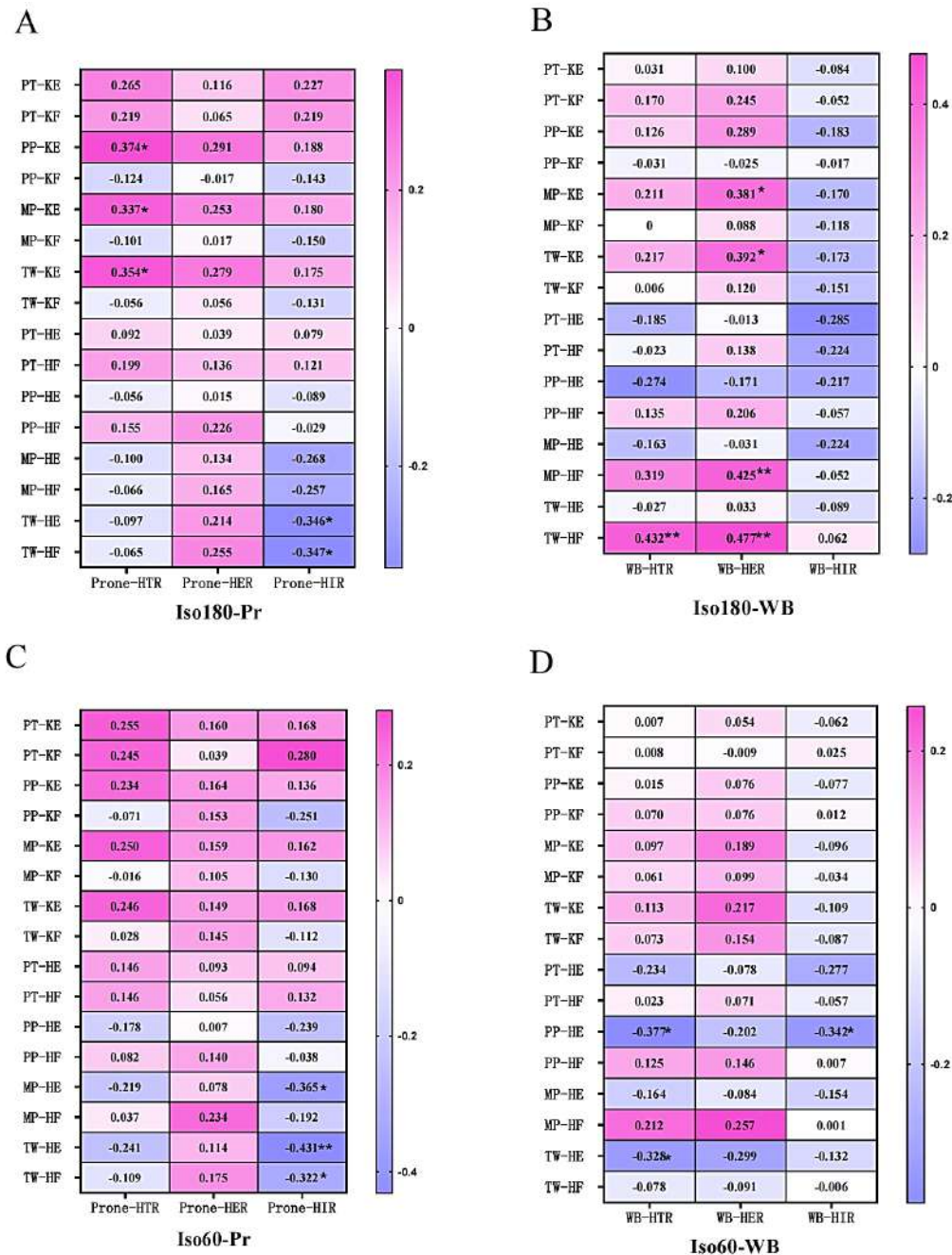
In the constant speed 60°/s test, the prone-HIR prone position hip internal rotation range of motion was significantly negatively correlated with the total work of the TW-HE hip extensor muscles ($r = -0.431, p < .01$), the total work of the TW-HF hip flexor muscles ($r = -0.322, p < .05$), and MP-HE hip extensor average power ($r = -0.365, p < .01$) (Figure 1C).

WB-HTR loaded hip joint total range of motion was significantly negatively correlated with TW-HE hip extensor total work ($r = -0.328, p < .05$), PP-HE hip extensor peak power ($r = -0.377, p < .01$) showed a significant negative correlation, and WB-HIR loaded hip internal rotation range of motion showed a significant negative correlation with PP-HE hip extensor peak power ($r = -0.342, p < .01$) (Figure 1D).

DISCUSSION AND CONCLUSIONS

Hip joint range of motion and lower limb isokinetic muscle strength are velocity-dependent

Testing at a slow angular velocity of 60°/s highlights the peak muscle force output. This study's results demonstrate a significant negative correlation between hip range of motion measurements in both prone and loaded positions and indicators of hip extensors and flexors. This indicates that during slow-speed hip movements, enhanced flexibility results in diminished stability, irrespective of the hip's anatomical or functional position. This significantly decreases the force output efficiency of the hip flexors and extensors. Aefsky et al., (2016) discovered in their study that slow isokinetic movements engage a greater proportion of the load range, necessitating muscles to withstand constant resistance, whereby joint stability emerges as a critical limiting factor in force output. In alpine skiing, athletes executing straight downhill movements primarily engage in isometric or slow concentric contractions of the lower limb muscle groups. This necessitates the continuous exertion of force by the active muscle groups to maintain slight flexion of both the hip and knee joints, thereby counteracting vibrations from the snow surface and stabilizing the support chain.



Note. A: Heat map analysis of the correlation between isokinetic testing at 180°/s and prone hip joint range of motion; B: Heat map showing the correlation analysis between constant speed testing at 180°/s and hip joint rotation range of motion under load; C: Heat map analysis of the correlation between isokinetic testing at 60°/s and hip joint rotation range of motion in the prone position; D: Heat map showing the correlation analysis between isokinetic testing at 60°/s and hip joint range of motion under load; Prone-HIR: Prone Hip Internal Rotation Range of Motion; Prone-HER: Prone Hip External Rotation Range of Motion; Prone-HTR: Prone Hip Total Rotation Range of Motion; WB-HIR: Weight-Bearing Hip Internal Rotation ROM; WB-HER: Weight-Bearing Hip External Rotation ROM; WB-HTR: Weight-Bearing Hip Total Rotation ROM; PT-KE: Peak Knee Extensor Torque; PT-KF: Peak Knee Flexor Torque; PP-KE: Peak Power of Knee Extensors; PP-KF: Peak Power of Knee Flexors; MP-KE: Mean Power of Knee Extensors; MP-KF: Mean Power of Knee Flexors; TW-KE: Total Work of Knee Extensors; TW-KF: Total Work of Knee Flexors; PT-HE: Peak Hip Extensor Torque; PT-HF: Peak Hip Flexor Torque; PP-HE: Peak Power of Hip Extensors; PP-HF: Peak Power of Hip Flexors; MP-HE: Mean Power of Hip Extensors; MP-HF: Mean Power of Hip Flexors; TW-HE: Total Work of Hip Extensors; TW-HF: Total Work of Hip Flexors; *: indicates a significant correlation at the 5% level; **: indicates a significant correlation at the 1% level.

Figure 1. Heat map showing the correlation analysis between hip joint ROM in two positions and isokinetic muscle strength indicators of the hip and knee joints at 60°/180° angular velocity.

Excessive flexibility of the hip joint during movement results in the muscles being positioned sub optimally for force generation, thereby disrupting the torque balance between the hip and knee and leading to compensatory losses in muscle strength. This phenomenon is more evident under conditions of low speed and high load. Secondly, testing at slow angular velocities predominantly engages slow-twitch muscle fibres, rendering it more appropriate for activities necessitating postural stability, such as when athletes sustain stability during low-speed gliding. Excessive hip joint range of motion (ROM) can lead to muscles being in a state of over-stretching or shortening, which is suboptimal for muscle contraction. Kwon et al. demonstrated that excessive internal rotation reduces the length of gluteus maximus muscle fibres to below 80% of the optimal length for force generation. This reduction diminishes cross-bridge coupling efficiency during slow contractions, leading to a decrease in extension force (Turnbull et al., 2009). This may elevate the load on the medial collateral ligament of the knee during skiing braking movements, as the suboptimal force generation of the hip extensor muscles compels the knee joint to accommodate greater deceleration torque.

Constant speed 180°/S loaded hip external rotation is an indicator of strong explosive power in both the hip and knee joints

An angular velocity of 180°/s indicates muscle explosive power. In alpine skiing, the hip joint is required to execute external rotation, internal rotation, and flexion/extension movements while under load to effectively adjust the direction of the skis and sustain body balance. The employed position measurement method in this study accurately represents the hip joint's range of motion under body weight and dynamic loads. The hip external rotator muscle group and the flexion/extension muscle group must collaborate during measurement to ensure stability and execute the movement, reflecting the dynamic control demands inherent in alpine skiing. The loaded position is more appropriate for evaluating the actual movement demands of alpine skiing than prone or seated positions. This study's results indicate a significant positive correlation between hip external rotation range of motion in the weight-bearing position and the average power and total work of both the knee extensor and hip flexor muscles (Figure 2). This finding demonstrates the substantial impact of hip external rotation range of motion on the efficacy of lower limb muscle group force production during weight-bearing activities. From a biomechanical perspective, in a weight-bearing posture, hip external rotation modifies the angle of the femur, aligning the force lines of the knee extensor muscle group, primarily the quadriceps, more closely with the axis of motion of the knee joint. This facilitates the efficient transmission of force produced by muscle contraction, thereby significantly minimizing force loss (Fu et al., n.d.; Iacobescu et al., 2024). Secondly, hip external rotation enhances the length-contraction range of the knee extensor muscles, which is closely associated with muscle work efficiency. The knee extensor muscle group is capable of achieving greater displacement work within the same time frame, thus significantly enhancing the average power and total work of these muscles (Yubin Lee & Chaegil Lim, 2023).

A significant positive correlation exists between weight-bearing external rotation range of motion and muscle function in hip flexors. The primary reason is the optimization of initial muscle length and improved coordination among muscle fibres and movement. The muscle length-tension relationship indicates that muscle fibres, when moderately stretched, achieve maximal cross-bridge formation between actin and myosin, leading to the highest rapid force production during contraction (Pawar et al., 2021). During hip external rotation, the femur's external rotation results in the outward movement of the lesser trochanter, which passively lengthens the muscle fibres of the hip flexors, particularly the iliopsoas muscle, to their optimal initial length for contraction, thereby significantly improving contraction efficiency. Simultaneously, the rectus femoris muscle, which spans both the hip and knee joints, undergoes decreased inhibition of hip flexion by knee extension as a result of improved knee joint mechanics during hip external rotation. This enables a greater emphasis on hip flexion, thereby enhancing the average power and total work output of the hip flexor muscles (Yan-Tao Ma et al., 2023).

The synergy between the hip and knee is essential in alpine skiing for executing high-quality turns, kick-snow, and other specialized manoeuvres (Shestakov et al., 2021). Hip external rotation enhances the range of motion for the hip flexors, mitigating joint compression. Additionally, the role of the hip flexors contributes to upward momentum for the knee extensors during kick-snow activities. The energy synergy produced by these three components markedly improves movement efficiency (Neumann, 2010). The synergistic effect is more evident under loaded conditions, as the loaded position replicates the body posture encountered during actual skiing. Hip external rotation depends on both the passive flexibility of the joint capsule and ligaments, as well as the active contraction control of the external rotator muscle group. The "*functional range of motion*" is more closely linked to the active force generation of lower limb muscle groups. This may elucidate the stronger correlation observed in the loaded position compared to the prone position.

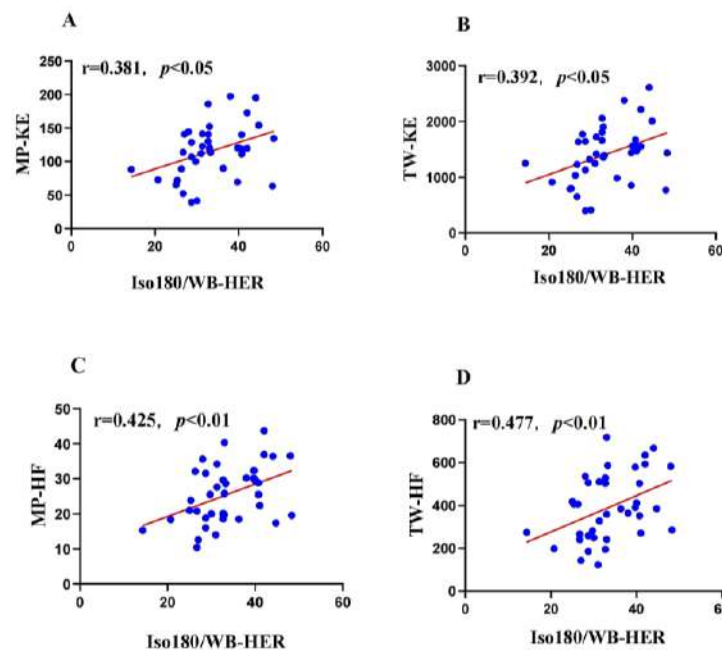


Figure 2. Scatter plot showing the correlation between 180°/S weight-bearing external rotation hip joint range of motion and isokinetic muscle strength indicators of the hip and knee joints.

Prone internal rotation at 180°/S or 60°/S is significantly negatively correlated with total hip extension and flexion work

This research demonstrated a significant negative correlation between prone internal rotation range of motion and indicators of hip extensor and flexor muscle strength as assessed through isokinetic muscle strength testing. A negative correlation was identified in both slow high-load and high-speed explosive conditions, indicating that an excessive range of internal rotation may adversely affect the force generation of the hip muscle group (Figure 3). The incompatibility of the static range of motion measurement method employed in this study with the dynamic functional requirements of alpine skiing-specific movements may account for this discrepancy. The prone hip joint range of motion measurement method evaluates the passive range of motion of the hip joint, primarily indicating the physiological flexibility of the joint capsule, ligaments, and internal rotator muscle groups. All specialized technical movements in alpine skiing occur under joint loading and dynamic conditions, necessitating the hip joint to coordinate rapid flexion, extension, and rotation while under load. Excessive passive internal rotation range of motion can hinder the hip joint's ability to maintain its optimal position for power generation during dynamic flexion and extension. In large-radius turns, the hip joint must sustain a specific external rotation angle to stabilize the centre of gravity. An excessive physiological

internal rotation range in an athlete may lead to excessive internal rotation of the femur, which shortens the lever arm between the hip extensor muscle insertion point and the muscle tension line, consequently diminishing torque output efficiency. Sandro Hodel and colleagues discovered that an increase in passive hip internal rotation range of motion correlates with an elevated load pattern of dynamic knee valgus (Hodel et al., 2025). This phenomenon is attributed to the relationship between femoral torsion and knee internal rotation adduction torque, aligning with the findings of this study (Dix et al., 2019; Imhoff et al., 2021). Dynamic eccentric control demands are prevalent in skiing movements; however, static assessment methods fail to address this aspect. During steep slope descent, athletes' hip muscles engage in rapid eccentric contractions to regulate the body's forward lean. Excessive internal rotation range of motion may compel the flexors to perform the dual functions of resisting internal rotation and facilitating hip flexion, resulting in a distribution of energy allocation and a reduction in the overall work accomplished by the flexors. Excessive activity of the internal rotators may disrupt the antagonistic function of the flexors and extensors. The hip flexor and extensor muscle groups exhibit a significant interactive relationship with the internal rotator muscle groups. Hip extension is primarily facilitated by the gluteus maximus, which plays a key role in hip external rotation. In contrast, hip flexion is dependent on the iliopsoas muscle, which is involved in both hip flexion and internal rotation. Excessive static internal rotation range of motion disrupts this balance, as evidenced by imaging and anatomical studies (Lieberman et al., 2006; Suthar et al., 2015). This is evident as an antagonistic effect during hip extension, wherein the gluteus maximus demonstrates a tendency for external rotation. Excessive internal rotation range of motion triggers compensatory contractions in internal rotator muscle groups, including the gluteus minimus, to restrict excessive internal rotation. This process directly hinders the concentric contraction efficiency of the gluteus maximus (Harris et al., 2017; Streeck, 2007). The iliopsoas muscle facilitates hip flexion and internal rotation; however, it necessitates moderate inhibition of external rotation muscle groups, including the piriformis, to prevent excessive movement during effective force generation (Boling et al., 2009). Excessive static internal rotation range of motion leads to increased basal tension in internal rotation muscle groups, which may result in coordination disorders of the iliopsoas muscle during rapid hip flexion.

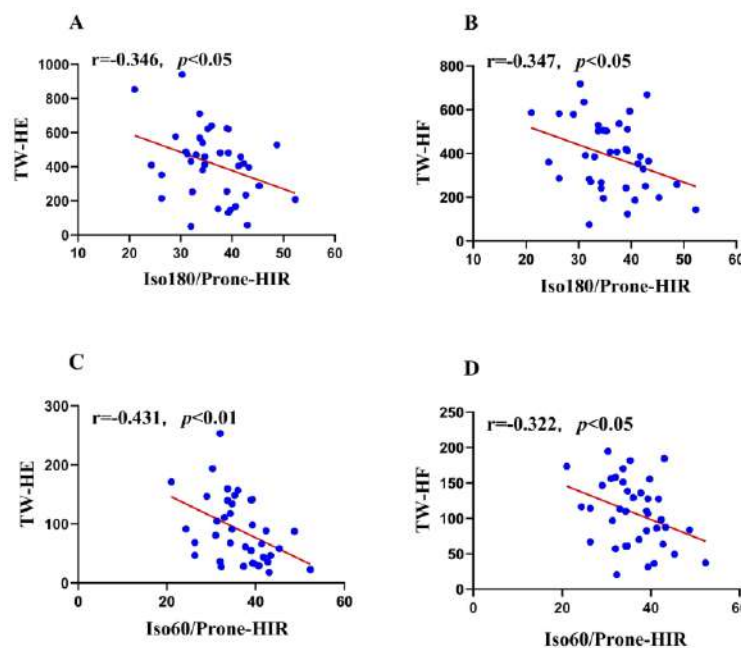


Figure 3. Scatter plot showing the correlation between prone internal rotation at 180°/S and 60°/S and the total work of hip extension and flexion.

Practical significance

This study examined the relationship between hip joint range of motion and the movements of the hip and knee joints at angular velocities of 60°/s and 180°/s in 21 elite male alpine ski athletes, demonstrating the significant impact of hip joint range of motion on the force output of the hip and knee. The findings hold significant practical implications for the training, assessment, and injury prevention of alpine ski athletes. This study's experimental results suggest that the loaded position should be incorporated into the evaluation of hip joint health and lower limb strength in athletes participating in this sport. Historically, clinical assessments of hip joint range of motion in athletes predominantly employed the prone position. However, this static evaluation method inadequately accounts for the athletes' physiological range of motion and may not accurately represent the functional demands imposed by the dynamic loads associated with alpine skiing. The hip external rotation range of motion in a weight-bearing position is the sole indicator in this study that demonstrates a strong correlation with both hip and knee joint explosive power, aligning more closely with the demands of rapid turns and snow-pushing movements in skiing. Incorporating this into the routine assessment system for alpine skiing athletes during training or screening is advisable. In designing lower limb strength exercises for alpine skiing athletes, it is essential for coaches to consider the interplay between hip joint flexibility and stability. In low-speed gliding or posture maintenance tasks, enhancing hip muscle control via anti-rotation or core stability training is advisable to reduce the negative impact of excessive range of motion on stability. Weighted external rotation training can enhance the active contraction capacity of the hip external rotator muscles during high-speed dynamic movements, thus improving the efficiency of explosive power output in the hip and knee joints.

Limitations

This research presents specific limitations. The study involved elite athletes; however, the sample size was limited and exclusively male, potentially leading to inadequate statistical power. Future research should increase the sample size and examine the potential impact of gender differences on these findings. This study primarily examined the univariate correlation between hip joint range of motion and isometric muscle strength of the hip and knee joints, without exploring multi-joint muscle co-activation patterns or intricate biomechanical mechanisms during dynamic movement. Future research should employ various perspectives to thoroughly examine the mechanisms connecting hip internal rotation range of motion with lower limb isometric muscle strength.

AUTHOR CONTRIBUTIONS

Conceptual design: Yupeng Yang (Y.Y.P.), Ying Li (L.Y.), and Mi Zheng (Z.M.); verification: Yupeng Yang (Y.Y.P.), Ying Li (L.Y.), and Mi Zheng (Z.M.); formal analysis: Yupeng Yang (Y.Y.P.), Ying Li (L.Y.); resources: Ying Qin (Q.Y.); data management: Yupeng Yang (Y.Y.P.), Ying Li (L.Y.); draft preparation: Yupeng Yang (Y.Y.P.); review and editing: Yupeng Yang (Y.Y.P.), Ying Li (L.Y.), Mengqi Liu (L.M.Q.); visualization: Mengqi Liu (L.M.Q.), Lisha Tian (T.L.S), and Qinghe Liu (L.Q.H.); supervision: Mi Zheng (Z.M.); project management: Mi Zheng (Z.M.); funding acquisition: Mi Zheng (Z.M.).

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

INSTITUTIONAL REVIEW BOARD STATEMENT

This study has been approved by the local ethics committee (approval number: 2025051), and all operations have followed the regulations stipulated in the Helsinki Declaration regarding human experiments.

INFORMED CONSENT STATEMENT

Informed consent was obtained from all subjects involved in this study.

DATA AVAILABILITY STATEMENT

Data generated or analysed during this study are available from the corresponding author upon reasonable request.

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Impact of a public physical activity program on the physical profile of older adults in Cali-Colombia

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ABSTRACT

Physical activity in older adults, depending on its frequency, intensity, and structure, yields favourable outcomes in mobility, mental agility, and overall quality of life. The aim of this study was to evaluate the impact of structured physical activity programs on the physical profile of older adults. Methods: A longitudinal repeated-measures design was conducted with 236 female participants aged 60 to 94, divided into two groups: short-term follow-up (6 weeks) and long-term follow-up (47 and 48 weeks). Results: Anthropometric evaluation revealed significant differences in weight and abdominal circumference among the short-term group, with moderate to high reductions ($r = 0.766$ for abdominal circumference; $d = -0.311$ for weight). In contrast, 50% of the participants in the long-term group showed moderate increases in these variables, in both frequency and upward trend. Functional capacity assessment using the Senior Fitness Test (SFT) showed small to moderate improvements in five of the six tests for the short-term group. However, in the second measurement, the walking time test revealed a deterioration in agility and functional speed. In the long-term group, lower-body flexibility improved, but a significant decline was observed in walking distance by the end of the evaluation ($d = -0.687$). While the program demonstrated positive potential, its overall impact was moderate in the short term and mild in the long term. Therefore, a structural redesign is recommended to promote sustained benefits, particularly by enhancing muscular strength as a key factor in functional autonomy during aging.

Keywords: Physical education, Physical activity, Older adults, Functional autonomy, Public program.

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INTRODUCTION

Physical activity offers well-documented benefits for both physical and mental health, making it an essential tool throughout the human life cycle—from early childhood to old age. It stimulates development and plays a vital role in the prevention of disease. Among older adults, a rapidly growing segment of the global population, well-structured programs and services have been shown to significantly contribute to overall well-being and alleviate the burden on public health systems (World Health Organization [WHO], 2024).

Globally, the older adult population is one of the fastest-growing demographic groups. According to projections by the United Nations (2023), by the year 2050 there will be more than 2.1 billion people over the age of sixty, driven by increasing life expectancy. This trend highlights the pressing need to promote healthy aging through the prevention of falls and the management of chronic disease, conditions often linked to sedentary lifestyles and poor health behaviours. The WHO (2023) estimates that regular physical activity among older adults could prevent approximately five million deaths annually and result in over twenty-seven billion dollars in savings on healthcare expenditures. Nevertheless, nearly 40% of adults over the age of seventy do not engage in sufficient physical activity to maintain or improve their physical and mental condition, thus negatively affecting their quality of life.

Sedentarism and physical inactivity, common in aging due to the natural decline in physiological reserve, are associated with a fragile health status characterized by the progressive deterioration of multiple bodily systems. This decline leads to the loss of functional capacity in terms of strength, aerobic endurance, agility, balance, flexibility, and reaction time (Castillo-Daza et al., 2024; Treacy et al., 2022). This functional loss is frequently accompanied by non-communicable diseases such as hypertension, diabetes, obesity, anxiety disorders, and depression, which are exacerbated in the absence of appropriate physiological stimuli (Al Nayf Mantas et al., 2022). Additionally, as noted by Dent et al. (2023), malnutrition—both undernutrition and overnutrition—is increasingly prevalent among older adults. This condition arises from multiple factors including age-related reductions in food intake and homeostatic mechanisms (Iglesias et al., 2020), and from food insecurity. Indeed, the WHO (2024) identifies poverty as a major risk factor for poor nutritional status and its associated consequences.

According to Martínez-De Haro et al. (2022), it is essential to understand the beneficial relationship between physical activity and individual health through a comprehensive assessment of well-being, particularly during stages of life in which morphological characteristics—such as those found in older adults—lead to identifiable strengths and limitations in carrying out daily activities (Barreto-De Lima et al., 2023). The benefits of structured physical activity programs for older adults have been extensively documented by Pacheco-Godoy et al. (2024), Fuertes-Paredes (2023), Pinheiro et al. (2022), and Mosqueda-Fernández (2021), among others. Through systematic reviews and effectiveness analyses, these researchers concluded that factors such as the type of activity, frequency, intensity, practice environment, intervention modalities, and participant motivation (Glejberman, 2023) are intrinsic elements that significantly contribute to favourable outcomes. These outcomes include improved mobility, reduced fatigue and waist circumference, enhanced mental agility, better sleep quality, and overall improvements in quality of life.

Given this broad spectrum of benefits—which transcend mere recreational participation—longitudinal research led by scholars such as Lisón-Loriente et al. (2025), Forero-Muñoz (2024), Varela-Gutiérrez & Rojas-Quirós (2021), Carvajal-Villanueva (2021), and Rodríguez-Calderón et al. (2021), among others, has highlighted the potential of long-term exercise interventions to improve physical fitness and thereby enhance the quality of life among older adults. These studies underscore the long-term sustainability of such benefits.

Consequently, and in light of the global context where lifestyle transformations have substantially altered patterns of physical activity, nutrition, and daily interactions (Flores-Olivares et al., 2021), the present study aimed to evaluate the impact of a publicly funded physical activity program on the physical health profile of older adults in Cali, Colombia.

MATERIALS AND METHODS

This study employed a longitudinal repeated-measures design to evaluate changes in physical capacities among older adults participating in public physical activity programs in the city of Cali, during the 2023–2024 period. These programs followed a systematic structure and were implemented under the names of *Cali en Forma* (2023) and *Activamente* (2024). On average, participants attended three sessions per week, each lasting approximately 60 minutes.

Each session began with basic flexibility and general joint mobility exercises, followed by a central phase consisting of music-based strength and endurance activities—with and without equipment—including dance routines, walking exercises, and various adaptations of these formats. The program was designed to promote exercise adherence through accessible, enjoyable, and functionally adapted routines, encouraging regular physical activity in safe, socially engaging, and motivational community environments.

Participants

The study involved 236 female participants, all selected from various groups across the city enrolled in public physical activity programs. Inclusion criteria required participants to be aged 60 years or older; to pass a medical fitness evaluation authorizing them to engage in physical activity; to be cognitively able to comprehend and follow instructions during both physical assessments and questionnaires; to sign the informed consent form; and to commit to completing both pre- and post-intervention evaluations to ensure the validity of the study. The intervention protocol was approved by the Ethics Committee of the *Institución Universitaria Escuela Nacional del Deporte* (IUEND).

The main researcher provided a detailed explanation of the study's objectives, potential benefits and risks, the confidential handling of participant data, and the nature of the assessments. Participants were given the opportunity to ask questions and express concerns before signing the informed consent form. Initial demographic data were collected, including full name, age, gender, and date of birth. To ensure data confidentiality, each participant was assigned a unique identification code, which they wore on a specially designed wristband. This research adhered to the ethical standards outlined in the Declaration of Helsinki (World Medical Association, 2024).

Procedure

Initially, participants underwent a medical screening using the Spanish version of the *Physical Activity Readiness Questionnaire Plus* (PAR-Q+), which is designed to identify potential health risks prior to engaging in physical activities or assessments. This instrument consists of seven health-related questions and serves to detect pre-existing medical conditions that may require further evaluation by healthcare professionals (Schwartz et al., 2019). To ensure data confidentiality and participant anonymity, each individual was assigned a unique identification code, which replaced all personal identifiers in subsequent data records and analyses.

In addition to physical performance, basic anthropometric measurements were obtained to complement the evaluation. Body weight was measured using a BC-585F FitScan® Tanita Body Composition Monitor, and

standing height was recorded using a Seca 213® stadiometer. Waist circumference (cm) was assessed with a non-elastic measuring tape at the midpoint between the lower rib margin and the iliac crest.

Following the initial screening, participants' physical fitness was assessed using the *Senior Fitness Test* (SFT), Spanish version (Ochoa-González et al., 2014), which has been validated in the Colombian older adult population (Cobo-Mejía et al., 2016). This battery evaluates various dimensions of functional fitness in older adults, including: a) lower- and upper-body strength; b) hamstring and lower-back flexibility; c) shoulder mobility and upper-body flexibility; d) dynamic agility and balance through the time taken to stand from a chair, walk eight feet, turn, and return to the chair; and e) aerobic endurance measured via the total distance walked in six minutes. The test includes normative tables that provide reference values based on age and sex-specific performance trends, which are recorded on a standardized data sheet (Rikli & Jones, 2013).

Two evaluation visits were scheduled for each of the five groups assessed, with varying time intervals between them to allow for short- and long-term change analysis. The instruments employed in this study have been previously validated in multiple investigations (Bonilla-Barrera et al., 2024; Rodríguez-Calderón et al., 2021; Carreres-Rey, 2021, among others). Assessments were conducted at each group's designated meeting location between 6:00 and 8:00 a.m., according to the following schedule:

- Group 1: November 23, 2023, and October 24, 2024
- Group 2: December 2, 2023, and October 30, 2024
- Group 3: September 24, 2024, and November 8, 2024
- Group 4: October 16, 2024, and November 29, 2024
- Group 5: October 22, 2024, and December 5, 2024

The evaluation process was directed and coordinated by the lead investigator. Administration of the PAR-Q+ was supported by resident physicians in Sports Medicine affiliated with the Health Services Institution (IPS) of the IUEND. For the application of the SFT, support was provided by physiotherapists, sports professionals, and nutritionists also affiliated with the IPS of the same institution.

Statistical analysis

Statistical analyses were conducted using R software, version 4.4.3 (2025-02-28), on a 64-bit Windows platform. The analysis followed a reproducible workflow, primarily using packages from the tidyverse ecosystem—including dplyr, tidyr, ggplot2, readxl, writexl, and broom—alongside specialized libraries such as rstatix and effect size for inferential testing and effect size estimation. Data were imported from Excel files and underwent a rigorous cleaning process, which included variable name standardization, data type conversion, and the replacement of erroneous values. Each individual observation was identified through a unique participant code, allowing for precise matching of pre- and post-intervention data.

Two matched groups were established for longitudinal analysis:

- Groups 1 and 2, composed of 76 participants, assessed at two points separated by 47 and 48 weeks, respectively.
- Groups 3, 4, and 5, comprising 160 participants, evaluated over a six-week follow-up period.

For all quantitative variables, descriptive statistics were calculated, including mean, median, standard deviation, minimum and maximum values, and interquartile ranges, disaggregated by group and time point. The normality of pre-post differences was assessed using the Kolmogorov-Smirnov test and Q-Q plots, which informed the choice of the appropriate statistical test. Specifically:

- If the differences followed a normal distribution, a paired Student's T-test was applied.
- If the distribution was non-normal, a Wilcoxon signed-rank test was used instead.

In all cases, the test statistic (t or W), p-value, statistical decision (with significance level $\alpha = .05$), and effect size were reported. Effect sizes were expressed as r for non-parametric tests and Cohen's d for parametric tests, calculated using functions from the effect size package. For variables showing statistically significant differences, individual change plots were generated, connecting pre- and post-values for each participant. Colour schemes were used to indicate the direction of change (i.e., improvement, decline, or stability).

Finally, the association between average participant age and functional changes was assessed using Spearman's rank correlation, due to the non-normal distribution of the data.

RESULTS

No participants were excluded from the study based on the PAR-Q+ questionnaire, as they all met the minimum safety criteria required to take part in the physical assessment sessions of this research. The demographic characteristics of the adults in the two long-term follow-up groups —47 and 48 weeks, respectively— indicated, first and foremost, a 100% female representation at both baseline and follow-up. The anthropometric characteristics, detailed in Table 1, provide insight into the participants' initial conditions and reveal notable changes over the observed periods. These data also help identify potential trends or outliers within each evaluated group.

Table 1. Anthropometric characteristics of the long-term follow-up group (47 and 48 weeks, respectively).

Statistic	Group 1–2 Baseline (22 Nov 2023 / 4 Dic 2023) (n = 76)	Group 1–2 Final (24 Oct 2024 / 30 Oct 2024) (n = 76)
Age (years)		
Mean $\pm$ SD	70.2 $\pm$ 7.3	71.1 $\pm$ 7.3
Median (IQR)	69 (12)	70 (11.25)
Min / max	60 – 88	61 – 89
Weight (kg)		
Mean $\pm$ SD	61.4 $\pm$ 5.05	62.4 $\pm$ 5.26
Median (IQR)	62.6 (7.9)	63.3 (7.85)
Min / max	49.5 – 69.6	50.8 – 69.9
Height (cm)		
Mean $\pm$ SD	154.4 $\pm$ 6.73	154.8 $\pm$ 6.89
Median (IQR)	154.4 (8.65)	155.0 (9.45)
Min / max	140.6 – 171.6	140.2 – 172.0
Abdominal circumference (cm)		
Mean $\pm$ SD	80.5 $\pm$ 5.09	82.9 $\pm$ 5.70
Median (IQR)	80.6 (7.28)	83.0 (6.25)
Min / max	69.0 – 91.2	66.5 – 98.0

Note: SD = standard deviation; IQR = interquartile range; Min = minimum; Max = maximum; cm = centimetres; kg = kilograms.

Regarding the results of the normality test, findings suggest that all variables should be analysed using the non-parametric Wilcoxon test (Table 2). The comparison tests, as shown in Table 3, revealed that age, weight, and waist circumference exhibited statistically significant changes, indicating relevant differences between the baseline and final assessments. In contrast, height ($p = .3643$) did not show statistically significant variation.

Table 2. Normality test results for anthropometric variables – Long-term follow-up groups (47 and 48 Weeks, respectively).

Variable	Kolmogorov-Smirnov <i>p</i> -value	Normality
Group 1–2. (22 Nov 2023 / 4 Dic 2023). (24 Oct 2024 / 30 Oct 2024). (n = 76)		
Age	1.14E-19	Non-normal
Weight	.03552	Non-normal
Height	8.01E-05	Non-normal
Abdominal circumference	.03264	Non-normal

Table 3. Comparison test results for anthropometric variables – Long-term follow-up groups (47 and 48 Weeks, respectively).

Group	Variable	Test	Statistic w	<i>p</i> -value	Decision	Effect size
Group 1–2 (22 Nov 2023/4 Dic 2023) (24 Oct 2024/30 Oct 2024) (n = 76)	Age	Wilcoxon	0	2.213E-17	Significant difference	0.973
	Weight		960	.009248	Significant difference	0.299
	Height		752	.05377	No difference	0.221
	Abdominal circumference		752	.0002317	Significant difference	0.422

Regarding the waist circumference variable, Figure 1 illustrates the individual changes from the beginning to the end of the study. The blue lines represent cases in which an increase was observed, which predominate both in number and in positive slope. This indicates that more than 50% of the participants experienced moderate increases in waist circumference. The red lines represent decreases, which were fewer in number and relatively smaller in magnitude.

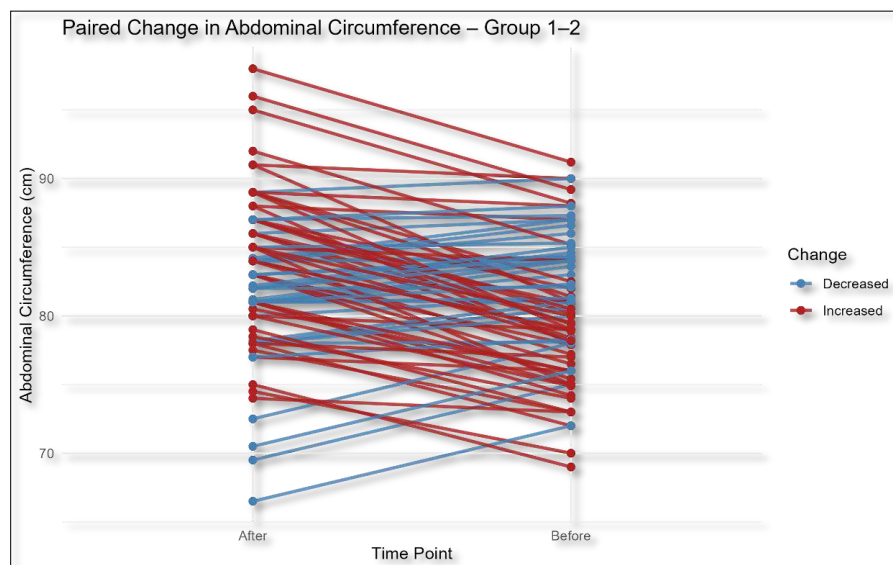


Figure 1. Individual changes in abdominal circumference in long follow-up groups, 47 and 48 weeks respectively.

In turn, the demographic and anthropometric results in Groups 3, 4, and 5, which were followed over a short-term six-week period, showed that the sex variable also revealed a female predominance at both time points, with 100% of participants being women. The age variable ranged between 74 and 75 years (Table 4).

Table 4. Anthropometric characteristics in short follow-up groups, six weeks.

Statistic	Group 3-4-5 Baseline	Group 3-4-5 Final
	(Sep 24/ 2024; Oct 16/ 2024 and Oct 22/ 2024) n = 160	(Nov 8/2024, Nov 29/ 2024 and Dic 5/2024) n = 160
Age (years)		
Mean $\pm$ SD	76.3 $\pm$ 7.96	76.5 $\pm$ 7.97
Median (IQR)	75 (14)	76 (13.25)
Min / max	60 – 94	60 – 94
Weight (kg)		
Mean $\pm$ SD	69.4 $\pm$ 13.93	69.1 $\pm$ 13.95
Median (IQR)	67.4 (21.0)	67.3 (21.0)
Min / max	45.6 – 106.2	45.9 – 105.6
Height (cm)		
Mean $\pm$ SD	154.2 $\pm$ 4.81	153.7 $\pm$ 4.92
Median (IQR)	154.2 (6.6)	153.9 (7.0)
Min / max	142.6 – 168	142 – 168
Abdominal circumference (cm)		
Mean $\pm$ SD	88.9 $\pm$ 12.82	85.5 $\pm$ 12.11
Median (IQR)	88.4 (16.1)	85.2 (15.2)
Min / max	57 – 117.5	57 – 115

Note: SD = standard deviation; IQR = interquartile range; Min = minimum; Max = maximum; cm = centimetres; kg = kilograms.

The results of the normality test for the short-term follow-up groups (Table 5) indicate that the variables age, height, and waist circumference did not follow a normal distribution (p -values < .05 in the Kolmogorov–Smirnov test), whereas weight was normally distributed (p > .05). This information was critical for selecting the appropriate statistical tests in the comparative analysis. Accordingly, non-parametric Wilcoxon tests were applied for age and waist circumference, while a parametric t -test was used for weight (Table 6).

Table 5. Results of normality test for anthropometric variables in short follow-up groups, six weeks.

Variable	Kolmogorov-Smirnov p -value	Normality
Group 3-4-5. (Sep 24/ 2024; Oct 16/ 2024 and Oct 22/ 2024) (Nov 8/2024, Nov 29/ 2024 and Dic 5/2024) (n = 160)		
Age	6.44E-34	Non-normal
Weight	.1918	Normal
Height	.002792	Non-normal
Abdominal circumference	.002858	Non-normal

Table 6. Comparison test results for anthropometric variables in short follow-up groups, six weeks.

Group	Variable	Test	Statistic w / t	p -value	Decision	Effect size
Group 3-4-5 (Sep 24/ 2024; Oct 16/ 2024 and Oct 22/ 2024) (Nov 8/2024, Nov 29/ 2024 and Dic 5/2024) n = 160	Age	Wilcoxon	0	1.64E-08	Significant difference	0.446
	Weight	t test	8720	.000102	Significant difference	-0.311
	Height	Wilcoxon	9180	1.88E-12	Significant difference	0.557
	Abdominal circumference	Wilcoxon	10576	3.22E-22	Significant difference	0.766

Statistically significant changes were observed in age—attributed to the natural passage of time rather than data errors—as well as in waist circumference, weight, and height at the end of the evaluation period (all with p < .05). The effect sizes ranged from small to moderate. For example, $r = 0.766$ for waist circumference,

suggesting a meaningful change, and Cohen's $d = -0.311$ for weight, indicating a slight to moderate decrease in the average value of this variable. It is important to clarify that the negative sign in the effect size indicates the direction of the change—namely, that mean weight decreased following the intervention.

With respect to the changes in waist circumference, Figure 2 shows a clear downward trend in this measure among most participants. The visual pattern supports the statistical comparison results, which revealed a significant difference with a moderate effect size, thereby strengthening the validity of the finding.

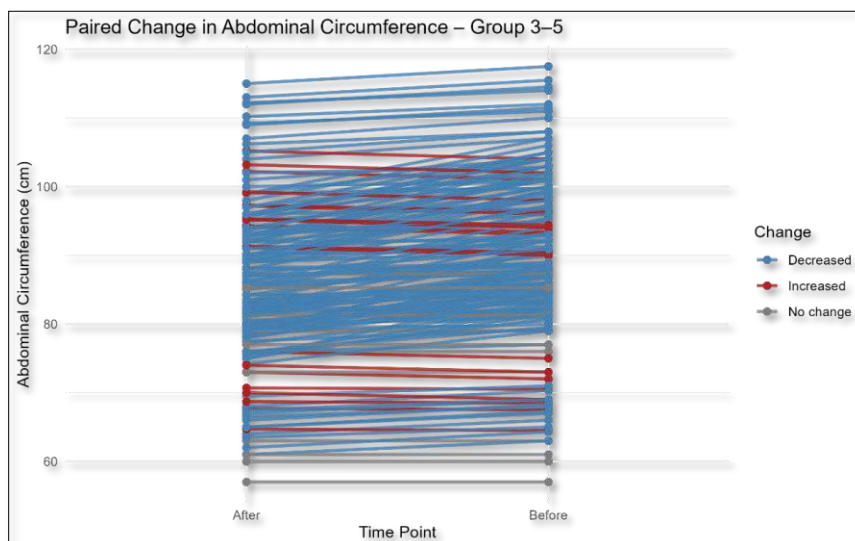


Figure 2. Paired change in abdominal circumference in short follow-up group, six weeks.

The physical performance outcomes, assessed using the Senior Fitness Test (SFT), validate the effectiveness and impact of the public physical activity programs. The results for Groups 1 and 2, followed over a long-term period of 47–48 weeks, are presented first and pertain to specific aspects such as flexibility, upper and lower limb muscle strength, joint mobility, and aerobic endurance, as measured by the components of the SFT (Table 7).

The normality tests, summarized in Table 8, show that most variables do not follow a normal distribution, based on the Kolmogorov–Smirnov test. The only exceptions were 6-minute walking distance ($p = .05887$) and chair stand test ($p = .09173$), which were normally distributed. This divergence in distribution justified the application of the Wilcoxon test for non-normal variables and the paired t-test for normally distributed variables.

About the comparison tests, two out of the six variables analysed did not show statistically significant differences between the baseline and follow-up measurements: back scratch (upper-body flexibility) and chair stand (lower-body strength). The 6-minute walk distance variable, however, showed a statistically significant difference, as assessed by a paired t-test ($p = 6.69E-08$), with a substantial effect size (Cohen's $d = -0.687$). The negative sign in the effect size indicates a reduction in the distance covered during the post-test, suggesting a deterioration in aerobic capacity and functional endurance among the participants. Other variables such as timed 8-foot walk, back scratch, bicep curls, and chair stand also exhibited improvements in mean scores (Table 9).

Table 7. SFT results in long follow-up groups, 47 and 48 weeks respectively.

Statistic	Group 1-2 Baseline (Nov 22/ 2023/Dic 4/ 2023) (n = 160)	Group 1-2 Final (Oct 24/ 2024 / Oct 30/ 2024) (n = 160)
Chair Sit-and-Reach (cm)		
Mean $\pm$ SD	-7.7 $\pm$ 11.2	-4.2 $\pm$ 7.1
Median (IQR)	-10 (12.25)	-2 (4.25)
Min / max	-23 / 31	-27 / 3
8-Foot Up-and-Go (s)		
Mean $\pm$ SD	8.38 $\pm$ 2.27	8.21 $\pm$ 2.90
Median (IQR)	8.49 (3.05)	7.77 (3.32)
Min / max	3.36 / 14.57	3.31 / 15.58
Back Scratch Test (cm)		
Mean $\pm$ SD	-5.5 $\pm$ 9.2	-8.1 $\pm$ 12.8
Median (IQR)	-2 (16.25)	-4 (23.25)
Min / max	-24 / 7	-40 / 7
6-Minute Walk Test (m)		
Mean $\pm$ SD	499.7 $\pm$ 72.0	454.8 $\pm$ 91.2
Median (IQR)	514 (117)	483 (111)
Min / max	342 / 613	249 / 615
Arm Curl (reps)		
Mean $\pm$ SD	17.1 $\pm$ 4.3	18.8 $\pm$ 4.1
Median (IQR)	17 (5.0)	19 (6.0)
Min / max	10 / 31	9 / 29
Chair Stand (reps)		
Mean $\pm$ SD	11.3 $\pm$ 4.2	12.3 $\pm$ 4.4
Median (IQR)	11 (5.25)	13 (5.25)
Min / max	2 / 23	1 / 22

Note: SD = Standard deviation; IQR = Interquartile range; Min = Minimum; Max = Maximum; cm = centimetres; kg = kilograms.

Table 8. Normality test results for sft variables in long follow-up groups, 47 and 48 weeks respectively.

Variable	Kolmogorov-Smirnov p-value	Normality
Group 1-2. (Nov 22/2023/Dic 4/2023) (Oct 24/2024/Oct 30/ 2024) (n = 19)		
Chair Sit-and-Reach	.0113	Non-normal
8-Foot Up-and-Go	2.81E-05	Non-normal
Back Scratch Test	.000727	Non-normal
6-Minute Walk Test	.05887	Normal
Arm Curl	.01569	Non-normal
Chair Stand	.09173	Normal

Table 9. Comparison test results for sft variables in long follow-up groups, 47 and 48 weeks respectively.

Group	Variable	Test	Statistic w / t	p-value	Decision	Effect size
Group 1-2 (Nov 22/2023/Dic 4/ 2023) (Oct 24/ 2024/Oct 30/2024) (n = 19)	Chair Sit-and-Reach	Wilcoxon	616	.0000891	Significant difference	0.449
	8-Foot Up-and-Go	Wilcoxon	2060	.002009	Significant difference	0.354
	Back Scratch Test	Wilcoxon	710	.2096	No difference	0.152
	6-Minute Walk Test	t test	5.9923	6.69E-08	Significant difference	-0.687
	Arm Curl	Wilcoxon	536	.000699	Significant difference	0.411
	Chair Stand	t test	-1.9483	.05533	No difference	0.23

In Groups 1 and 2, the correlation analyses did not reveal any statistically significant associations between age and any of the physical or anthropometric variables. All correlation tests yielded p -values greater than .05, indicating that age had no linear effect on these measures. These findings suggest that the detected changes in the variables were not influenced by age variability within this group.

The Senior Fitness Test (SFT) results for Groups 3, 4, and 5, who underwent short-term follow-up (six weeks), demonstrate evident changes between the initial and final assessments during this brief period (Table 10).

Table 10. SFT results in short follow-up groups, six weeks.

Statistic	Group 3-4-5 – Baseline (Sep 24/2024, Oct 16/2024 and Oct 22/2024) n = 160	Group 3, 4 y 5 – Final (Nov 8/2024, Nov 29/2024 and Dic 5/2024) n = 160
Chair Sit-and-Reach (cm)		
Mean $\pm$ SD	-9.1 $\pm$ 9.13	-0.29 $\pm$ 17.83
Median (IQR)	-9.0 (14.25)	-0.5 (30.0)
Min / max	-39 / 3	-39 / 31
8-Foot Up-and-Go (s)		
Mean $\pm$ SD	8.56 $\pm$ 2.98	8.75 $\pm$ 2.61
Median (IQR)	8.28 (2.83)	8.58 (2.96)
Min / max	3.19 / 22.51	3.20 / 17.78
Back Scratch Test (cm)		
Mean $\pm$ SD	-15.5 $\pm$ 12.51	-12.8 $\pm$ 10.90
Median (IQR)	-16.0 (17.0)	-13.0 (12.0)
Min / max	-46 / 14	-45 / 7
6-Minute Walk Test (m)		
Mean $\pm$ SD	314.6 $\pm$ 112.06	392.3 $\pm$ 97.15
Median (IQR)	322.0 (99.0)	410.0 (93.25)
Min / max	7 / 563	85 / 582
Arm Curl (reps)		
Mean $\pm$ SD	17.42 $\pm$ 4.39	17.75 $\pm$ 7.26
Median (IQR)	18.0 (5.0)	16.0 (6.0)
Min / max	2 / 28	5 / 42
Chair Stand (reps)		
Mean $\pm$ SD	11.35 $\pm$ 3.32	11.83 $\pm$ 3.10
Median (IQR)	12.0 (5.0)	12.0 (4.0)
Min / max	2 / 18	2 / 18

Note: SD = Standard deviation; IQR = Interquartile range; Min = Minimum; Max = Maximum; cm = centimetres; kg = kilograms.

The Kolmogorov–Smirnov normality tests (Table 11) determined that none of the variables followed a normal distribution; all p -values were below .05. Consequently, non-parametric Wilcoxon signed-rank tests were used for comparisons across all variables. Statistically significant differences were found in five of the six variables evaluated.

Lastly, in Groups 3, 4, and 5, statistically significant correlations were identified between participant age and the magnitude of individual change (pre/post) in certain physical and anthropometric variables. The strongest correlation was found for improvement in the chair sit-and-reach flexibility test ($r = 0.30$; $p < .001$), indicating a moderate positive association—older participants showed greater gains in this physical capacity. Similarly, a low positive correlation was observed in the back scratch test ($r = 0.20$; $p = .011$), suggesting that older adults also tended to experience more improvement in upper-body flexibility.

Conversely, body weight showed a weak negative correlation with age ($r = -0.18$; $p = .022$), indicating that younger participants were more likely to experience reductions or smaller increases in weight. Additionally, a low positive correlation was found between age and change in height ($r = 0.21$; $p = .006$). Together, these findings suggest that age had a mild to moderate influence on some of the observed changes, particularly those related to flexibility (Table 12).

Table 11. Normality test results for sft variables in short follow-up groups, six weeks.

Variable	Kolmogorov-Smirnov p-value	Normality
Group 3-4-5. (Sep 24/2024, Oct 16/2024 and Oct 22/2024) (Nov 8/2024, Nov 29/2024 and Dic 5/2024) n = 40		
Chair Sit-and-Reach	1.1E-06	Non-normal
8-Foot Up-and-Go	.000904	Non-normal
Back Scratch Test	.008677	Non-normal
6-Minute Walk Test	.003442	Non-normal
Arm Curl	4.74E-08	Non-normal
Chair Stand	2.63E-05	Non-normal

Table 12. Comparison test results for sft variables in short follow-up groups, six weeks.

Group	Variable	Test	Statistic w	p-value	Decision	Effect size
Group 3-4-5 (Sep 24/2024, Oct 16/ 2024 and Oct 22/ 2024) (Nov 8/2024, Nov 29/2024 and Dic 5/2024) n = 40	Chair Sit-and-Reach	Wilcoxon	2422	.00000118	Significant difference	0.384
	8-Foot Up-and-Go	Wilcoxon	2738	1.535E-08	Significant difference	0.459
	Back Scratch Test	Wilcoxon	2374	9.179E-08	Significant difference	0.422
	6-Minute Walk Test	Wilcoxon	2086	9.113E-13	Significant difference	0.572
	Arm Curl	Wilcoxon	4722	.1568	No difference	0.113
	Chair Stand	Wilcoxon	1706	.000663	Significant difference	0.269

DISCUSSION

Based on the general objective of assessing the impact of structured physical activity programs in older adults, the initial demographic data indicated that participants ranged in age from 60 to 94 years. This finding aligns with data from the United Nations (n.d.), which highlights that women outnumber men at older ages due to their longer life expectancy, with a global average of 74 years. In 2022, women represented 55.7% of individuals aged 65 and over worldwide.

In this context, the anthropometric evaluations revealed one of the most relevant findings: a significant variation in waist circumference across both evaluated groups, although in opposite directions. While the short-term follow-up group (six weeks) exhibited a mean reduction of approximately two centimetres, the long-term follow-up group (47 and 48 weeks) showed a comparable increase. This divergence suggests that, in the short term, physical activity programs may produce a positive initial impact on cardiometabolic health, as also reported by Varela-Gutiérrez and Rojas-Quirós (2021). Similarly, the waist circumference reduction parallels findings from Pacheco-Godoy et al. (2024), who observed improvements in participants engaging in virtually guided and regularly supervised exercise. These outcomes reinforce the notion that participant engagement and perceived evaluation—particularly during early phases—can enhance outcomes. However, in the absence of sustained stimuli, behavioural reinforcement, or individualized interventions, long-term benefits may be attenuated.

With regard to functional performance, assessed through the SFT, the short-term group demonstrated statistically significant changes in five out of six tests. These small-to-moderate improvements suggest that even a six-week period is sufficient to induce positive functional adaptations when programs are implemented systematically (Pinheiro et al., 2022; Mosqueda-Fernández, 2021). Nevertheless, the 8-foot walk test, which assesses agility and functional speed, showed contradictory results. Despite statistical significance, the increased time recorded in the post-test indicates a decline in agility, potentially related to daily variability, accumulated fatigue, or uncontrolled environmental factors during testing.

In contrast, the long-term group sustained improvements in lower-body flexibility, supporting the idea that continued training stimuli can maintain specific physical capacities. However, the group experienced a significant decline in aerobic capacity, as measured by the 6-minute walk test. This finding suggests that even with ongoing participation, multiple factors may influence cardiorespiratory performance in older adults, including age-related physiological decline (Al Nayf Mantas et al., 2022), intermittent dropout, comorbidities, or loss of adherence to the intensity required for physiological progression.

When comparing these results with similar studies, the functional fitness levels observed in this study's groups fall within expected ranges for physically active older adults in Latin America, although in some cases, they remain below values reported for special populations. For instance, in the short-term group, the mean 6-minute walk distance was 392.3 meters, which does not surpass the sarcopenia risk threshold of <408.5 meters proposed by Barreto-De Lima et al. (2023) in Brazil and is lower than the 512 ± 89 meters reported by Castillo-Daza et al. (2024) among Colombian police retirees enrolled in structured programs. This discrepancy may reflect differences in training intensity, baseline fitness levels, or participant commitment to the program.

Regarding upper-body strength, the average number of bicep curls in both groups —17.4 and 17.7 repetitions in the short-term group; 17.1 and 18.8 in the long-term group— was comparable to national and Latin American studies that have utilized the SFT (Castillo-Daza et al., 2024). These values are well above the sarcopenia risk threshold for women, defined as 11.5 repetitions. Similarly, the improvement in lower-body flexibility, from -9.0 cm to -0.2 cm in the short-term group, is consistent with the results reported in successful interventions such as Nordic walking (Paou et al., 2019) and resistance band training programs (Sánchez-Roa et al., 2024), which have documented gains of 20–28% in this functional component. This trend suggests that the evaluated program has positive potential, especially in the short term, although its effects appear to diminish over longer follow-up periods —possibly, as mentioned earlier, due to the challenges in sustaining motivation, adherence, and adequate training intensity over time. These findings should be interpreted within the realistic constraints of community-based programs, where material conditions, methodological variability, and environmental factors may substantially influence the observed outcomes.

The variation in outcomes between the short- and long-term follow-up groups raises important questions about the factors influencing the effectiveness of physical activity programs for older adults. Interestingly, it was the group with the highest average age —median of 75–76 years in Groups 3, 4, and 5— that demonstrated the greatest functional improvements, with statistically significant changes in five out of six SFT measures. In contrast, the younger group —median age of 69–70 years in Groups 1 and 2— exhibited more modest gains. A potential explanation may lie in the "*observer effect*", whereby the perception of being evaluated may have more strongly influenced the short-term group, due to the shorter time span between baseline and post-testing. This could have generated increased motivation, leading participants to improve attendance, increase effort during sessions, or even engage in more physical activity outside of the formal

program. This type of adaptive response, however, is difficult to maintain over time, potentially explaining why the long-term group, despite participating for nearly a year, showed fewer functional gains.

Although this study identified some beneficial outcomes from the public physical activity program, such as improvements in upper- and lower-body flexibility and a significant reduction in waist circumference in the short-term group, the overall impact was modest, particularly when compared with similar interventions conducted in other settings. Studies from Europe, North America, and Latin America have reported greater gains in lower-body flexibility, muscular strength, and aerobic endurance (Fernández-Rodríguez et al., 2024). These programs, despite having similar durations and frequencies, achieved stronger outcomes across multiple SFT domains, raising critical questions about the training intensity, progression, and overall design quality of the program evaluated here (Fuentes-Paredes, 2023; Pinheiro et al., 2022; Mosqueda-Fernández, 2021).

While statistically significant improvements were recorded in five out of six SFT tests for the short-term group, the effect sizes were small to moderate. In the long-term group, a decline in aerobic capacity, as measured by the 6-minute walk test, was even observed. These disparities may be attributed to low physical demand, lack of individualized or progressive training, or insufficient ongoing evaluation, all of which have been identified as key determinants of intervention effectiveness in older adults (Fernández-Rodríguez et al., 2024).

CONCLUSIONS

The findings of this study demonstrate that the public physical activity program evaluated in an older adult population produced positive but modest impacts on both anthropometric and physical performance variables. The most notable result was the significant reduction in waist circumference in the short-term follow-up group (six weeks). In contrast, the long-term follow-up group (47 and 48 weeks, respectively) showed an increase in this measurement, suggesting that initial benefits may dissipate over time in the absence of complementary strategies to support adherence, supervision, and progression of the exercise stimulus.

From a physical performance perspective, the short-term group exhibited significant improvements in five out of six SFT components, particularly in upper- and lower-body flexibility and aerobic capacity. However, a decline in agility was identified—specifically in the 8-foot up-and-go test. In contrast, the long-term group maintained improvements in only four of the six SFT domains and showed a notable deterioration in aerobic capacity, reinforcing the notion that the training stimulus was insufficient or poorly adapted in terms of intensity and progression.

When compared with international evidence, these results suggest that the benefits achieved by the program were lower than those reported in similar interventions conducted in Latin America and Europe. Programs of equal or shorter duration have demonstrated more robust improvements in physical fitness, highlighting possible weaknesses in the methodological design, planning, or execution of the public program assessed in this study.

It is therefore concluded that, while the evaluated program has real potential for impact, especially in the short term, its effects were inconsistent and not sustained over time. The limited improvements observed in strength-related tests indicate that the strength training component requires reassessment and enhancement. Ensuring appropriate volume, frequency, type, and progression of strength stimuli is critical to

translating physical activity sessions into measurable and sustained improvements in the overall health of older adults. Current scientific evidence supports the central role of strength training in the prevention of multiple aging-related chronic diseases, such as sarcopenia, osteoporosis, type 2 diabetes, and cardiovascular disease. Improvements in muscular strength are not only essential for maintaining functional independence, but also strongly associated with increased longevity and reduced incidence of hospitalizations and falls.

This underscores the urgent need to revise the content, intensity, methodology, and evaluation mechanisms of public exercise programs, incorporating progressive adjustments, individualized training plans, systematic feedback, and sustained participant motivation. Only through these structural improvements can the full benefits of physical activity in older adults be realized and interventions be clinically meaningful, physically relevant, and sustainable over time.

This study provides a valuable foundation for future research and public interventions, as it identifies both the strengths and limitations of community-based physical activity programs for older adults. Expanding this line of inquiry to other settings, with larger and more diverse samples, would significantly contribute to understanding the true and potential impact of these strategies on the health of aging populations. Moreover, implementing such programs at a larger scale, with technical and academic support, could generate broader and more sustainable public health benefits, especially in urban Latin American contexts, where population aging and chronic disease prevalence are increasing.

Consequently, and given the widespread presence of similar public programs at the national level, it is recommended that relevant institutions strengthen or redesign the content, methodologies, and operational processes that guide physical activity initiatives for older adults. This requires continuous monitoring, intensity tracking, sustained intervention strategies, and updated staff training, in addition to tailored adjustments based on age, sex, and initial functional level of participants.

It is also recommended that complementary components —such as educational sessions on nutrition and quality of life, periodic feedback, and progressive exercise plan adaptations— be integrated into the program to enhance long-term outcomes. Only through such measures can the extensive body of evidence on the benefits of physical exercise for older adults be translated into consistent, lasting, and clinically significant improvements within both local and national contexts.

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Loss aversion under pressure: Analyzing decision-making in high-stakes tennis through Grand Slam big data

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ABSTRACT

This study examines loss aversion behaviour in professional tennis, with a focus on players' responses to high-stakes situations such as game points and break points. While prior research has provided valuable insights, it has predominantly relied on limited match samples, often confined to select tournaments or individual players. To address this limitation and enhance the generalizability of findings, the present study employs a comprehensive dataset comprising ten years (2010–2020) of five-set matches from all four Grand Slam tournaments. Anchored in Prospect Theory—which suggests that individuals are more motivated to avoid losses than to acquire equivalent gains—the analysis investigates key performance indicators including scoring success rate, serve ace rate, and double fault frequency. The results indicate that players exhibit loss-averse behaviour in specific contexts, notably by reducing double faults during break points. However, other performance metrics, such as ace rates and serve accuracy, do not consistently reflect loss-averse tendencies. A post-hoc analysis based on point differentials further elucidates the nuanced manifestations of loss aversion across varying match contexts. These findings contribute to a more robust understanding of risk-related decision-making in elite sports and offer implications for performance optimization and athlete management.

Keywords: Loss aversion, Prospect theory, Tennis, Serve performance, Risk aversion, Player behaviour, Game points, Break points.

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INTRODUCTION

The Loss Aversion Theory (LAT) is a significant concept arising at the intersection of economics and psychology, explaining that people assign different weights to equivalent amounts of gains and losses. Specifically, individuals exhibit a stronger tendency to avoid losses than to pursue gains. Despite placing greater weight on losses, people tend to be risk-seeking in the domain of losses and risk-averse in the domain of gains (Kahneman & Tversky, 1979).

Although numerous studies providing evidence for the existence of loss aversion, scepticism remains among researchers about whether individuals consistently assign greater weight to losses across different contexts (Anbarci et al., 2018). For instance, previous research suggests that the tendency for loss aversion may not manifest depending on the level of prior experience and expertise (List, 2003; Levitt & List, 2008).

Therefore, previous studies have been conducted to examine whether loss aversion tendencies arise in decision-making or behaviour under controlled conditions, particularly in fields where skill and expertise are guaranteed, such as professional sports. In response to scepticism regarding loss aversion, previous research conducted field research using data from professional golfers (Pope & Schweitzer, 2011). The study verified that golfers exhibit loss aversion tendencies in actual games. Golfers were found to concentrate more in the loss domain: they were significantly less accurate in putts for "*birdie*" (one stroke under par) or "*eagle*" (two strokes under par) compared to similar putts for "*par*" or above (e.g., "*bogey*" for one stroke over par or "*double bogey*" for two strokes over par). This trend was consistent even among experienced professional golfers.

Therefore, the extant research validated loss aversion among professional golfers in the US Open tournaments (Elmore & Urbaczewski, 2021). Their analysis of data from 11 US Open tournaments revealed that top golfers exhibited substantial loss aversion behaviours. Additionally, Anbarci et al. (2018) examined loss aversion behaviours in tennis, finding that players took more risks with serve speed when trailing in points or rankings.

Greve et al. (2021) identified that soccer players were less sensitive to gains and losses in the loss frame. The study demonstrated that even in top-division matches in European soccer leagues, players showed a decrease in rational decision-making regarding fouls and an increase in loss-averse behaviour, explained by prospect theory.

However, there are lack of comprehending the mechanisms of loss aversion behaviour from a few studies due to the varying contexts of decision-making in different sports and the types of data collected in field research.

In this regard, insights gained from prospect theory can aid in identifying the conditions under which player perform optimally and those under which they encounter difficulties, highlighting the need for further research to understand player' decision-making patterns. However, many studies tend to focus on specific situations or general trends without adequately considering situational factors, thereby limiting the applicability of their findings.

In dynamic sports such as tennis, match conditions can change rapidly. Therefore, it is essential to conduct inquiries and various analyses that adequately reflect these dynamic changes and address potential issues. Conducting tailored research that considers match conditions can deepen our understanding of tennis

players' decision-making and performance, contributing to the development of training and strategies that lead to practical improvements.

Thus, this study aims to verify loss aversion behaviour in tennis games based on prospect theory. Tennis is a sport where individual skill, strategy, and psychological state play crucial roles. During matches, players continuously make decisions to maintain their service games and break the opponent's serve to gain an advantage for victory (Anbarci et al., 2018). In such decisions, both risk and reward coexist, and the Loss Aversion Theory provides critical insights into how players respond in these situations.

Against this backdrop, the objective of this study is to identify biased decision-making and behaviours in tennis players through a comprehensive understanding of prospect theory, thereby suggesting strategic directions for performance improvement. The specific aims of the research are as follows:

First, the study seeks to thoroughly understand the characteristics of tennis and define loss-averse decision-making within the context of match situations. Previous studies that identified loss-averse behaviours in tennis players often had limitations, such as viewing the player's serve as a single measurement variable without adequately considering the specific characteristics of the sport. This study aims to overcome these limitations by obtaining more comprehensive data to enhance the understanding of loss-averse situations in tennis matches.

Second, the study aims to verify the tendencies of loss aversion in tennis players. This will be accomplished through the collection and analysis of actual match data. Based on these findings, the study will propose strategic directions for players.

The structure of this study is that chapter 2 provides an understanding of prospect theory and the concept of loss aversion, reviewing prior research to identify areas that need further exploration. Chapter 3 presents the hypotheses formulated to achieve the research objectives and describes the data collection and analysis procedures. Chapter 4 details the results of the data analysis. Lastly, chapter 5 derives implications from the research findings.

Research background and hypotheses

For this study we define server' and receiver' gain and loss as Table 1. The fundamental assumption of this study is that, in loss situations, players exert greater effort to avoid losses, which subsequently leads to outcomes such as scoring points and improving serve success rates. Based on prior research, this study defines gain and loss situations for both the server and receiver. For the server, a gain situation refers to a game point, where winning one point secures the game, while a loss situation occurs when losing a point results in losing the game. In contrast, the definitions for the receiver are the opposite.

Table 1. Operational definition.

Definition		
Server	Gain	Game point situation where winning one point secures the game
	Loss	Break situation where losing one point results in losing the game
Receiver	Gain	Break situation where winning one point secures the game
	Loss	Game point situation where losing one point results in losing the game

The feeling of loss experienced by the server when losing a point in a break situation, thereby conceding the game, is likely to be greater than the value of winning a point in a game point situation to secure the game.

Similarly, for the receiver, the sense of loss in a game point situation, where losing a point result in losing the game, is expected to be greater than the value of winning a point to defend the game.

Literature review

Prospect Theory emphasizes that decision-makers do not always behave rationally due to bounded rationality in the decision-making process (Kahneman & Tversky, 2013). They point out the limitations of expected utility theory and introduce a value function that is concave in gains and convex in losses. This provides the insight that losses of the same magnitude have a greater impact than equivalent gains.

In traditional economics, the value curve $T(x)$ reflects equal gains and losses for the decision-maker, where the perceived value by the decision-maker is the same. In other words, the happiness derived from a gain and the pain caused by a loss of the same magnitude cancel each other out, leading to $T(x) = x$.

As shown in Figure 1, in behavioural economics, the value curve $V(x)$ shows that when the point lies on the positive half-axis of xxx, the decision-maker's behaviour is based on gains, while when the point lies on the negative half-axis of xxx, it reflects losses. For points A (x_1, y_1) and C (x_3, y_3), where $|x_1| = |x_3|$ and $|V(x_3)| > |V(x_1)|$, it holds that the pain from losses is significantly greater than the pleasure from equivalent gains.

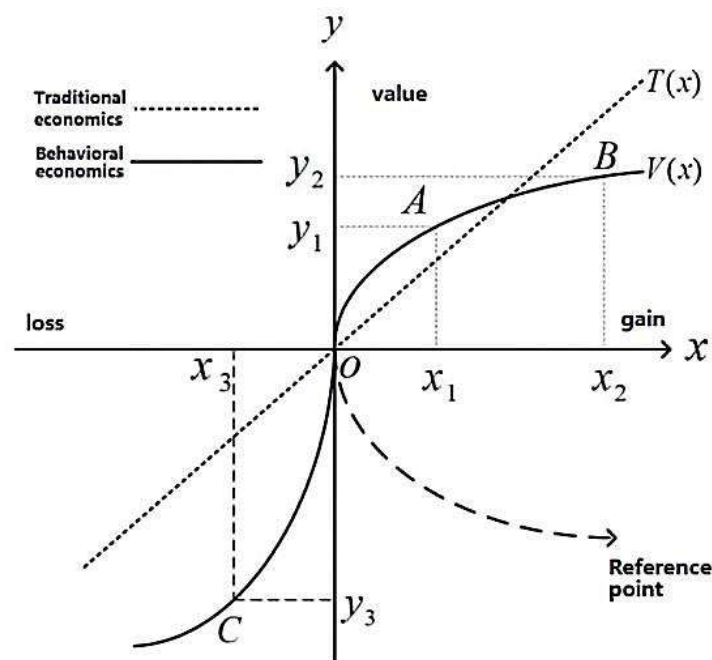


Figure 1. Value function of loss version (adopt from Liu et al., (2021)).

People do not evaluate gains or losses based on their absolute value, but rather in comparison to their personal reference point (Liu et al., 2021). The reference point can be adjusted depending on the circumstances, and the adjusted reference point serves as the basis for decision-making, potentially shifting the inflection point.

Therefore, prospect Theory can help in understanding player' decision-making processes and emotional responses in the sports field. By applying the theory to explain player' loss-averse behaviour, it can be suggested that player tend to avoid losses based on their personal reference point regarding match

outcomes. This reference point influences how player perceive and evaluate their own performance, subsequently affecting their strategic choices and psychological state during the match.

In previous research, Apesteguia & Palacios-Huerta, (2010) found that the score at the time of the shot. That is, the intermediate score as a reference point with the team taking the first kick in a penalty shootout having a 60.5% probability of winning.

Furthermore, past records, opponents and performance may serve as a reference point, influencing loss-averse behaviour. For example, Anderson & Green, (2018) found that a player's personal best score serves as a reference point in the chess game. Players exert more effort to set higher score, but after achieving a new higher score, players tend to give up at higher rates and for longer periods. This suggests that players are highly motivated when trying to surpass their past performance, but once they reach new higher score, they tend to adopt a less challenging attitude.

Pawlowski, (2021) empirically analysed the impact of opponents' performance, past performance, and expectations on player' effort and performance, treating these factors as reference points. According to Pawlowski, (2021), reference points impacting loss-averse behaviour in sports include opponent skill levels, psychological expectations, and player's past performance. For example, baseball batting averages or marathon completion times, the decimal point can act as significant reference points for player' loss-averse behaviour. Additionally, individual psychological attitudes and thought processes can also serve as reference points.

Furthermore, previous study found that bronze medallists appeared to be happier than silver medallists. This phenomenon is explained by the psychological concept of counterfactual thinking, where bronze medallists view their reference point as the fourth-place finish without a medal, while silver medallists perceive their reference point as losing the gold medal (Medvec et al., 1995).

In the realm of tennis game, Anbarci et al., (2017) provided empirical evidence that loss aversion behaviour occurs in player, particularly in tennis. When a server falls behind in points, the servers exert more effort on their serves, but as the score gap widens, this effort diminishes. This effect was more pronounced in male player than in females.

Furthermore, previous research finds that female players were significantly more likely than male players to withdraw due to concerns about COVID-19. Even after accounting for cross-country differences in preferences such as trust, patience, and risk-taking, women still exhibited higher levels of pandemic-related aversion. The model attributes about 15% of the probability of withdrawal to gender, highlighting a clear gender gap in risk aversion during the pandemic (Kowalik & Lewandowski, 2021).

Cary & Stephens, (2023) revealed that high-earning women exhibit greater risk aversion, particularly related to COVID-19. Additionally, the study highlights that women were notably more risk-averse regarding international travel during the pandemic. However, Lowrance et al., (2020) found no evidence of behaviour consistent with loss aversion predictions for either gender.

Mallard, (2016) found that both male and female players exhibited loss aversion in tennis matches, as their serve accuracy decreased when they were in the lead. Players showed a tendency to choose relatively safer serves when leading, which can be viewed as a behaviour stemming from the psychological motivation to maintain their lead. However, the analysis lacked insights into whether loss aversion tendencies were

moderated by critical moments in the match or the player's career. Moreover, the study primarily relied on internal factors (i.e., the player's mindset) to explain the reasoning behind the player's decisions, neglecting potential external factors influencing their choices.

Apart from gender differences, Krawczyk, (2019) posited out faster serve speeds were interpreted as an indication of greater effort, but he argued that faster serves might not necessarily reflect more effort. Instead, they could signify a player's intention to reduce effort. Additionally, Krawczyk highlighted the oversight of ignoring the crucial role of the receiver in tennis, which plays a significant part in the dynamics of serve-and-return interactions.

Although previous study provides many insights, the study primarily used serve speed as the main measure of player effort, but some scholars argue that serve speed may not fully reflect the effort expended by players (Anbarci et al., 2018). While serve speed plays a critical role in understanding gender differences in loss aversion, there is some disagreement over how to interpret these differences. Critics have noted that focusing on serve speed as an effort indicator is limiting, as it may not comprehensively represent overall effort.

Therefore, while various related studies have been conducted, limitations persist due to insufficient data and the lack of clear definitions of server loss and gain situations. To address these issues, this study attempts to overcome the limitation of using only serve speed as an indicator of effort by utilizing various indicators. Additionally, previous research focuses solely on gender differences without considering various individual factors. In this regard, this study draws on data from all major tournaments, which feature diverse players in different environments. Moreover, previous research is lack of understanding of psychological responses to external factors. Thus, the study controls for performance differences by using data exclusively from five-set matches. Lastly, the extant research shows utilizing insufficient data and unclear definitions of server loss and gain situations. Considering the limitation, this study employs data from all four major tournaments and defining server loss and gain situations through theoretical lens of loss aversion theory in tennis matches.

Hypotheses development

According to loss aversion theory, the emotional impact of losing a point in break point situations is significantly greater than in game point situations. The server, aware of the higher potential for loss, is likely to play more cautiously and strategically, minimizing errors to avoid losing the game. As a result, the server's winning percentage is expected to be higher in break point situations due to heightened focus and careful play. Hence, we hypothesize.

Hypotheses 1. The server's winning percentage will be higher in break point situations than in game point situations.

Loss aversion theory suggests that the potential loss in break point situations creates a heightened sense of urgency for the server. To avoid losing the game, the server may opt for faster and stronger serves, aiming to score aces directly. Since an ace is a direct and efficient way to win a point, the server is likely to attempt and succeed at more aces in break point situations to avoid the psychological burden of a potential loss. Hence, we hypothesize.

Hypotheses 2. The first serve ace rate for the server will be higher in break point situations than in game point situations.

Loss aversion theory posits that the fear of losing due to a failed serve is more pronounced in break point situations compared to game point situations. As a result, the server is expected to focus more on accuracy, aiming to land their first serve successfully. Since a successful first serve increases the likelihood of securing

the point, the server is likely to concentrate more on ensuring the first serve is accurate, resulting in a higher first serve success rate during break point situations. Hence, we hypothesize.

Hypotheses 3. The first serve success rate for the server will be higher in break point situations than in game point situations.

Loss aversion theory explains that the fear of losing due to a double fault is greater in break point situations because a double fault directly leads to conceding the game. To avoid this outcome, the server is likely to play more cautiously, ensuring that double faults are minimized. The need to prevent such costly errors should lead to a significantly lower double fault rate in break point situations compared to game point situations. Hence, we hypothesize.

Hypotheses 4. The server's double fault rate will be lower in break point situations than in game point situations.

Based on loss aversion theory, the psychological burden of losing due to a failed first return is greater in game point situations compared to break point situations. The receiver, aware of the stakes, is likely to concentrate more on successfully returning the opponent's first serve. This heightened focus on avoiding loss should result in a higher first serve return success rate in game point situations, as the receiver seeks to capitalize on the opportunity to break the server's momentum. Hence, we hypothesize.

Hypotheses 5. The receiver's first serve return success rate will be higher in game point situations than in break point situations.

METHODS AND MATERIALS

Data collection

For this study, we identify five key indicators to verify the stronger tendency for loss aversion in loss situations compared to gain situations. These indicators enable a thorough analysis of various aspects of tennis matches, enhancing the validity of the findings by leveraging a comprehensive dataset.

To test our hypotheses, data was gathered on four variables: server's scoring percentage, first-serve ace rate, first-serve success rate, and double-fault frequency. For Hypothesis 5, we employed the receiver's first serve return success rate. These five datasets were sourced from matches that went to five sets over the past two decades in the four Grand Slam tournaments (Australian Open, French Open, Wimbledon, and the US Open), as provided by tennisabstract.com. A total of 188 five-set matches and 61,473 points from the 2010s to the 2020s were included in the analysis. Table 2 presents the distribution of data collected under game point and break point situations.

Table 2. Data description.

	N(%)
Game point	11931 (71.8)
Break point	4692 (28.2)
Total	16623 (100)

Analysis procedure

To assess dynamic loss aversion in tennis match scenarios, this study employed a Z-test for independent sample proportions. The objective of this test is to compare two distinct proportions. Since the dataset is

sufficiently large, there was no need for a homogeneity of variance test, and the Z-test was chosen as an appropriate method to identify significant differences between the groups.

To test hypothesis 1, the server's scoring percentage is employed, comparing game point and break point situations to assess whether the scoring rate is significantly higher in break points. This allows us to determine if loss aversion leads to improved performance in break (loss) scenarios.

For hypothesis 2, we used the first-serve ace rate, dividing the data into game and break points, then comparing the rates. By doing so, we can identify whether the first-serve ace rate increases significantly in break points, which would indicate a loss aversion effect.

Considering hypothesis 3, the first-serve success rate is examined by categorizing the data by game and break point situations. A comparison is made to evaluate whether the first-serve success rate is significantly higher during break points, indicating a tendency to avoid losses.

For Hypothesis 4, the double-fault rate is evaluated across game and break points. The analysis helps to confirm if the double-fault rate is significantly lower in break points, reflecting a strategic reduction in errors in high-pressure situations due to loss aversion.

Lastly, for Hypothesis 5, the receiver's first-serve return success rate is used and separating the data by game and break points and comparing the success rates. This analysis determines if the return success rate is higher during game points, consistent with a loss aversion tendency in game point scenarios.

RESULTS

The analysis results of this research are presented in Table 3. Considering the results, the server's scoring success rate was compared between game point and break point situations. The success rate in game points was 0.655, whereas it was 0.617 in break points. The Z-test yielded a Z-score of -4.571 and indicating a significant difference ($p < .001$). However, the result contradicted our hypothesis, which expected a higher success rate in break point situations. Hence, H1 is rejected.

Table 3. Z-test results between game point and break point groups.

Variables		Sample proportion	SE	Z-score	Sig. (p)	Result
Server's scoring success rate	Game point	0.655	-0.008	-4.571	2.43E-06*** (Reversed)	Rejected
	Break point	0.617				
First-serve ace rate	Game point	0.101	0	0	-8.644	Rejected
	Break point	0.062				
First-serve success rate	Game point	0.619	0	-0.061	.475	Rejected
	Break point	0.619				
Server' double-fault rate	Game point	0.093	0.008	2.112	.017*	Supported
	Break point	0.077				
Receiver's first-serve return rate	Game point	0.899	0.019	-2.041	.021* (Reversed)	Rejected
	Break point	0.938				

Note. SE: Standard Error. Sig. or p-value: Statistical significance probability (the probability that the observed result is due to chance). *: $p < .05$ (statistically significant at the 5% level). **: $p < .01$ (statistically significant at the 1% level). ***: $p < .001$ (statistically significant at the 0.1% level, highly significant).

The results shows that the ace rate during game points was 0.101, while it was 0.062 during break points. However, H2 was not statistically significant. We examined the first-serve success rate, which was identical at 0.619 for both game point and break point situations. The Z-score is -0.061 ($p = .475$), indicating no significant difference. Hence, H3 was rejected. The double-fault rate was compared to examine hypothesis 4, revealing a rate of 0.093 in game points and 0.077 in break points. The Z-test produced a Z-score of 2.112 ($p < .05$) and is statistically satisfied. Hence, H4 was supported.

Last, for Hypothesis 5, the receiver's first-serve return success rate was compared. In game points, the success rate was 0.899, and it was 0.938 during break points. The Z-score was -2.041, with a p -value of .021, indicating a significant difference ($p < .05$). However, this result also contradicted the initial hypothesis, which predicted a lower return success rate in break point situations. Hence, H5 was rejected.

Overall, the results revealed a significant result regarding the server's double-fault rate. The double-fault rate was lower in break points than in game points, demonstrating a tendency for loss aversion. However, the server's scoring rate, ace success rate, and first-serve success rate did not exhibit loss aversion, and the receiver's first-serve return success rate showed the opposite result.

Double faults, as actions that occur without interaction with the opponent, reflect a loss aversion pattern similar to that seen in golf. On the other hand, the scoring rate, ace rate, and first-serve return success rate are strongly influenced by the opponent that may explain why loss aversion is less apparent in tennis. Despite the high stakes of break point situations for servers and game point situations for receivers, their respective success rates were not higher.

Notably, even though the study focused on closely matched players in five-set matches to minimize errors, significant results were not obtained for all hypotheses. This suggests that although the psychological impact of a server or receiver losing a point in these critical situations may be greater than the satisfaction of the opponent, this emotional impact does not necessarily translate into higher scoring or success rates in actual play.

Post-hoc analysis

To better understand loss aversion in tennis, further research should establish dynamic criteria for gain and loss situations in the sport. The difference in loss aversion between tennis, with its opponent interaction, and individual sports like golf stems primarily from the dynamic and interactive nature of tennis. As players continually adjust their reference points based on the situation, future studies should consider defining reference points in a dynamic manner to assess loss aversion more accurately.

Hence, we further conducted post-hoc analysis using z-tests by dividing game point and break point situations for both servers and receivers into groups based on point differentials: larger point differential group (Group 1 and Group 3) and smaller point differential (Group 2 and Group 4). This analysis aimed to explore how loss aversion manifests in dynamic situations such as the server's scoring and ace performance under game and break points, as well as the receiver's performance in these critical moments.

Post-hoc analysis result

Table 4 illustrates that between game point and break point situations, further subdividing each into two groups based on score differences and presents the ratios for five key indicators. Examining the server's scoring success rate, it was 0.674 in Group 1, 0.634 in Group 2, and 0.655 in game point situations. In Group

3, it was 0.633, 0.609 in Group 4, and 0.617 in break point situations. The server's scoring success rate is higher in game point situations and tends to decrease slightly during break points.

Next, looking at the server's ace success rate, it was 0.12 in Group 1 and 0.079 in Group 2. In game point situations, it was 0.101, while in Group 3, it was 0.063, and both Group 4 and break point situations recorded 0.062. This indicates that the server's ace success rate is highest during game points and relatively lower during break points.

As for the server's first serve success rate, it was 0.613 in Group 1, 0.627 in Group 2, and 0.619 in game point situations. In Group 3, it was 0.629, 0.614 in Group 4, and 0.619 in break point situations, indicating that the first serve success rate remains relatively consistent.

Regarding the server's double fault rate, it was 0.103 in Group 1 and 0.08 in Group 2. In game point situations, it was 0.093, while in Group 3 it was 0.072, 0.079 in Group 4, and 0.077 during break points. The double fault rate tends to be slightly lower in break point situations compared to game points.

Table 4. Success rates of server and receiver metrics by situation.

	Group1 40-0, 40-15	Group2 40-30, AD-40	Game point	Group3 0-40, 15-40	Group4 30-40, 40-AD	Break point
N	6304	5627	11931	1567	3125	4692
Scoring ratio (Server's point-winning percentage)	0.674	0.634	0.655	0.633	0.609	0.617
Server's ace success rate	0.12	0.079	0.101	0.063	0.062	0.062
First serve success rate (Serve success rate)	0.613	0.627	0.619	0.629	0.614	0.619
Server's double fault ratio	0.103	0.08	0.093	0.072	0.079	0.077
First return success rate (Receiver's first return success rate)	0.880	0.921	0.899	0.937	0.938	0.938

Table 5. Differences between groups based on score differences in gain situations.

Variables		Sample proportion	SE	Z-score	p-value
Server's point-winning percentage	Group1	0.674	0.009	4.635	1.78E-06***
	Group2	0.634			
Server's ace success rate	Group1	0.12	0.006	7.371	8.49E-14***
	Group2	0.079			
Server' first serve success rate	Group1	0.613	0.009	-1.572	.058
	Group2	0.627			
Receiver's first return success rate	Group3	0.937	0.001	-0.704	.241
	Group4	0.938			

Note. SE: Standard Error. ***: $p < .001$ (statistically significant at the 0.1% level, highly significant).

Finally, examining the receiver's first return success rate, it was 0.880 in Group 1 and 0.921 in Group 2. In game point situations, it was 0.899, while in Group 3, it was 0.937, and both Group 4 and break point situations recorded 0.938. This shows that the receiver's first return success rate is higher during break point situations.

The results of the Z-test conducted to analyse the differences in ratios between groups based on score differences in gain situations (server's game points and receiver's break points) are presented in Table 5.

In gain situations (server's game point and receiver's break point), a comparison between the group with a larger score difference (Group 1) and the group with a smaller score difference (Group 2) revealed the following: first, for the server's scoring success rate, Group 1 had a success rate of 0.674, while Group 2 had a success rate of 0.634. The Z-test yielded a Z-score of 4.635 ($p < .001$), indicating a significant difference. A similar comparison was made for the server's ace success rate between the two groups. Group 1 showed an ace success rate of 0.12, while Group 2's ace success rate was 0.079. The Z-test result was a Z-score of 7.371 ($p < .001$), demonstrating a significant difference. In terms of the server's first serve success rate, Group 1's success rate was 0.613, while Group 2's was 0.627. The Z-test showed a Z-score of -1.572 ($p = .058$), indicating no significant difference. For the receiver's first return success rate, a comparison between the group with a larger score difference (Group 3) and the group with a smaller score difference (Group 4) was conducted. Group 3's first return success rate was 0.937, while Group 4's was 0.938. The Z-test produced a Z-score of -0.704 ($p = .241$) showing no significant difference.

Next, the comparison of ratio differences between the group with a larger score difference (Group 3) and the group with a smaller score difference (Group 4) in loss situations (server's break point and receiver's game point) is presented as shown in Table 6.

Table 6. Differences between groups based on score differences in gain.

Variables		Sample proportion	SE	Z-score	p-value
Server's point-winning percentage	Group 3	0.633	0.015	1.587	.056
	Group 4	0.609			
Server's ace success rate	Group 3	0.063	0.010	0.104	.458
	Group 4	0.062			
Server's first serve success rate	Group 3	0.629	0.015	0.989	.161
	Group 4	0.614			
Receiver's first return success rate	Group 2	0.921	0.014	2.962	.002**
	Group 1	0.880			

Note. SE: Standard Error. **: $p < .01$ (statistically significant at the 1% level).

For the scoring success rate between the group with a larger score difference (Group 3) and the group with a smaller score difference (Group 4), Group 3's scoring success rate was 0.633, while Group 4's was 0.609. The Z-test resulted in a Z-score ($p = .056$), indicating no significant difference. A similar comparison was performed for the server's ace success rate between the two groups. Group 3's ace success rate was 0.063, and Group 4's ace success rate was 0.062. The Z-test produced a Z-score of 0.104 ($p = .456$), showing no significant difference. Regarding the server's first serve success rate, Group 3 had a success rate of 0.629, while Group 4's was 0.614. The Z-test gave a Z-score of 0.989 ($p = .161$), indicating no significant difference. Finally, a comparison of the receiver's first return success rate was made between the group with a larger score difference (Group 2) and the group with a smaller score difference (Group 1). Group 2's first return success rate was 0.921, while Group 1's was 0.880. The Z-test showed a Z-score of 2.962 ($p < .01$), indicating a significant difference.

Thus, the analysis results indicates that in game point situations, the server's scoring success rate and ace success rate are higher in the group with a larger score difference (Group 1) compared to the group with a smaller score difference (Group 2). It can also be observed that servers exhibit a stronger tendency for loss

aversion in gain situations (game points), particularly in groups with a larger score difference. Additionally, in game point situations where the server is leading significantly, the sense of loss from failing to secure the point and win the game is perceived as greater than the sense of loss experienced when leading by a smaller margin and allowing the situation to reach deuce.

DISCUSSION

The goal of this study is to apply prospect theory to tennis matches by defining gain and loss situations, analysing how players exhibit loss aversion tendencies during matches, and exploring how these tendencies affect actual match outcomes. By doing so, the study seeks to strengthen the evidence of loss aversion behaviour presented in previous research and contribute to a deeper understanding of loss aversion tendencies in tennis matches.

Unlike golf, tennis is a competitive sport between two players, where match outcomes are determined by whether a player successfully holds their serve or breaks the opponent's serve. Therefore, the sense of loss experienced by players must be dynamically designed to align with the characteristics of tennis matches. Since the score directly influences the outcome, players strive to minimize mistakes during critical points or game situations, which tends to amplify loss aversion. This study is designed under the assumption that players exert greater effort to avoid losses in loss situations, and this effort manifests in metrics such as scoring success rate and serve success rate.

Based on prior research, the study defines scoring and loss situations for both servers and receivers. For servers, a scoring situation is a game point, where winning a point results in winning the game, while a loss situation is one where losing a point results in losing the game. For receivers, the reverse applies. Servers are likely to perceive the sense of loss from conceding a break point as greater than the value of winning a point during a game point situation. Similarly, receivers will feel that the loss of a point during a game point situation, leading to losing the game, is greater than the value of winning a point and holding their serve.

The analysis results showed that the server's double fault rate was significantly lower in break point situations compared to game point situations. This suggests that players perceive the loss from a double fault to be greater in break point situations and thus actively minimize double faults in such scenarios, confirming this behavioural tendency. However, the hypotheses were rejected for the other indicators, excluding the double fault rate. To reassess these findings, the groups were reclassified based on score differences for further analysis. The results revealed that in game point situations, servers in the group with a larger score difference had higher scoring success rates and ace success rates compared to those in the group with a smaller score difference. This indicates that servers exhibit a stronger tendency to avoid losses even in gain situations (game points) when leading by a larger margin. Specifically, when the server is leading by a significant margin in game point situations, the sense of loss from failing to win the point and conceding it is perceived to be greater than the sense of loss from allowing the game to reach deuce when leading by a smaller margin.

Academic implication

This study aims to scientifically explain the impact of psychological factors on game performance by applying Prospect Theory to tennis matches and analysing players' decision-making patterns. Prospect Theory emphasizes that people have a strong tendency to avoid losses, which becomes more pronounced in dynamic sports like tennis. While previous studies have focused on general tendencies or specific situations, this study takes a more detailed and comprehensive approach by analysing various metrics using data from major tennis tournaments. By conducting customized research that considers the psychological

characteristics of tennis players and game situations, this study seeks to overcome the limitations of previous research. This approach not only offers insights into decision-making analyses that account for psychological factors in tennis but also suggests the potential for its application in other sports, making significant contributions to the fields of sports psychology and performance optimization.

Additionally, this study analyses data from five-set matches over 20 years in the four major tennis tournaments, aiming to empirically demonstrate how players experience psychological pressure during crucial moments in a match and how this pressure affects their decision-making. By achieving a more accurate understanding of players' decision-making patterns during matches, this research will serve as valuable foundational material for future studies on the impact of psychological factors on game performance.

In terms of analysis, this study analysed data from five-set matches over 20 years in the four major tennis tournaments to empirically demonstrate how players experience psychological pressure during crucial moments in a match and how this pressure affects their decision-making. Various metrics such as scoring success rate, serve success rate, return success rate, unforced errors, serve aces, and rally win rates are used to quantify players' psychological responses, and the psychological value of points in game point and break point situations is compared and analysed. This approach emphasizes the importance of empirical research, enabling a more precise and effective strategy formulation and player management.

In particular, this study contributes to understanding the psychological pressure players experience during critical moments in tennis matches and the complexity of decision-making that follows by analysing big data from all major tournaments. Analysing only a portion of the major tournaments could result in biased outcomes, so comprehensive analysis of data from all major tournaments was conducted to derive more reliable results. This helps develop strategies that stabilize players' psychological states during matches and lead to optimal performance.

Practical implication

First, this study provides contributions to optimizing player performance by providing concrete data that coaches and players can use to improve training and strategies. Through customized research that considers the characteristics of each tournament and the psychological factors specific to each player, coaches can tailor training and strategies to optimize player performance. This helps in understanding how players can perform better in certain situations and identify the circumstances where issues arise. Additionally, by analysing decision-making in high-pressure situations, coaches can gain insight into how players manage psychological pressure, which in turn can aid in developing training methods that foster greater psychological resilience.

Second, since decisions made during critical moments of a match can significantly influence the outcome, understanding players' tendencies toward loss aversion helps in comprehending how they evaluate risk and reward in decision-making. By empirically demonstrating this, the study provides valuable support for coaches and players in managing psychological pressure during key moments in matches and developing strategies that maximize performance. This not only contributes significantly to the fields of sports psychology and performance optimization but also provides specific data that can drive actual performance improvements, enabling more precise and effective approaches to game strategy and player management.

Finally, this study contributes to understanding the psychological pressure players experience during critical moments in tennis matches and the complexity of decision-making that follows. It provides insights that can help develop strategies to stabilize players' psychological states during matches and lead to optimal

performance. This data-driven approach suggests the potential for applying Prospect Theory to decision-making analysis not only in tennis but also in other sports. By enabling more precise and effective approaches to game strategy and player management, this study makes a significant contribution to the fields of sports psychology and performance optimization.

Limitation and future research

While the findings of this study provide practical guidelines that can enhance actual performance in tennis matches, there are several limitations. First, the data are limited to specific situations, making it difficult to generalize the results. Second, there may be missing variables that are necessary to fully explain loss aversion tendencies. Tennis is a sport where direct competition with an opponent and psychological battles are crucial. It demands quick actions and fast decision-making, requiring players to rapidly respond to their opponent's actions and adjust their strategies. Therefore, loss aversion in tennis can vary depending on the interaction with the opponent, significantly influencing the player's psychological state and strategy. Future research should consider more diverse match situations and additional variables for a more comprehensive analysis.

Additionally, while this study primarily focused on scoring and success rates, it is important to quantitatively analyse players' psychological states and the resulting behavioural changes. A comprehensive approach incorporating biometric signals or psychological measurements would be necessary for this. Furthermore, comparative studies with other sports could offer valuable insights into how loss aversion tendencies manifest differently depending on the type of sport.

AUTHOR CONTRIBUTIONS

WY. K. designed, reviewed, and analysed the articles and contributed to the writing of the manuscript. SK.J and JH.K reviewed the articles and contributed to the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data are available upon request.

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Gender differences in fair play behaviours in elite handball: Evidence from World Championship teams

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ABSTRACT

This study aims to examine whether fair play behaviour is associated with competitive performance. An additional objective is to analyse gender differences in Fair Play in the Handball World Championships between 2007 and 2023. A total of 464 games were reviewed to analyse the team's fair play statistics. The Mann-Whitney U test was used to determine any differences between the men's and women's teams on the variables analysed in the study. Statistical power analysis, G*Power 3.1, was used to determine the power statistical analysis and the effect size of the model. According to the team rankings, significant differences were observed between men and women in all variables analysed, except for yellow cards. The findings indicate that teams achieving higher final rankings generally demonstrated more disciplined conduct. These results support the idea that fair play is positively associated with athletic performance, reinforcing the notion that ethical and disciplined behaviour is compatible with competitive success.

Keywords: Handball performance, Final ranking, Gender, Behaviour.

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INTRODUCTION

Sport has long been recognised as an important component of the educational process, contributing significantly to the development of interpersonal communication and social skills (Izquierdo et al., 2021; Graupensperger et al., 2018) as well as supporting the overall personal development of individuals, especially during formative years. Due to its global reach, sport influences cultural norms, educational approaches, and the formation of values and behaviours among young people (Simon et al., 2018). It is a multidimensional phenomenon that promotes values relevant not only in sports but also in everyday life, such as respect, responsibility, integrity, and fairness. When properly guided, sport has been shown to foster prosocial behaviours and moral development (Zhu et al., 2025). Within this context, Fair Play emerges as a key ethical principle. Officially recognised in the Olympic Charter, it represents a central mission of the International Olympic Committee. In recent years, however, sport has faced a growing crisis of values. Instances of misconduct, rule violations, and unethical behaviour aimed at gaining unfair advantages have become increasingly common (Pelegrín Muñoz, 2005; Pelegrín, Serpa, & Rosado, 2013), highlighting the difficulty of promoting prosocial behaviour in high-pressure, result-driven environments. Research has shown that when athletes become fixated on winning at all costs, they tend to adopt a tense and reactive playing style, relying less on strategy and more on aggression, often leading to unethical or inappropriate conduct (Pelegrín, Serpa, & Rosado, 2013). Although such behaviours are generally considered unacceptable, they are sometimes tolerated or even encouraged in pursuit of athletic success (Bohdan & Kowalik, 2022). A study by Fruchart & Rulence-Pâques (2014), involving professional and amateur handball players, found that most professional considered actions like pushing an opponent justifiable in certain situations. According to the authors, this may be partly due to the frequent physical contact inherent in sport, which can shape how athletes perceive and evaluate aggressive behaviour. Similarly, excessive pressure from external sources (Kang, Kim, & Lee, 2021) and overconfidence in one's abilities have also been associated with unethical or antisocial behaviour (Pelegrín et al., 2013). These findings suggest that the competitive nature of the sport can often compromise ethical standards and increase the likelihood of morally questionable conduct (Pilz, 2005). Within the field of sports and exercise sciences, understanding the psychological foundations of Fair Play is essential for encouraging ethical behaviour and positive social interactions in competitive settings. One of the most widely studied constructs in this regard is moral disengagement, which refers to a set of cognitive mechanisms that individuals use to justify unethical or harmful actions, reducing their sense of personal responsibility (Hodge & Gucciardi, 2015; Stanger et al., 2013). In sports, moral disengagement has been linked to various forms of antisocial behaviour, including aggression and the use of performance-enhancing substances (Bandura, 1991; Ring & Kavussanu, 2018). These behaviours are often rationalised by athletes who prioritise outcomes over ethics (Boardley & Kavussanu, 2009). Research has also shown that athletes with more aggressive profiles tend to express higher levels of anger and hostility, especially when they experience frustration or negative evaluation (Forsdike & O'Sullivan, 2022; Lazarević et al., 2014; Pelegrín et al., 2013). Moreover, athletes driven by high levels of extrinsic motivation, such as the pursuit of rewards, recognition, or social comparison, are more likely to adopt these types of behaviours (Boardley & Kavussanu, 2009).

Conversely, constructs such as empathy and moral identity have been positively associated with Fair Play and prosocial behaviour (Kavussanu et al., 2013; Kavussanu & Boardley, 2009). Empathic Athletes demonstrate a greater ability to understand the emotions and perspectives of others, which contributes to more respectful and cooperative behaviour during competition. Recent evidence suggests that empathy-based interventions can be effective in reducing aggressive tendencies (Stanger et al., 2012). For instance, male athletes who participated in an empathy-focused training program reported lower intentions to act aggressively toward opponents (Stanger et al., 2012). This behavioural complexity becomes particularly

evident in high-intensity, physically demanding team sports such as handball (HB). As a fast-paced, high-scoring indoor contact sport, HB exposes players to frequent physical collisions and elevated emotional stress (Fritz et al., 2020). While physical contact is permitted within the rules, especially, especially by defenders attempting to block attackers, such conditions often give rise to conflict and tension, increasing the risk of rule violations and sanctionable behaviours. As in many other team sports (Vansteenkiste et al., 2014; Junge et al., 2000), Fair Play in HB is a dynamic and context-dependent phenomenon. It is influenced by situational factors, such as the match score, a player's position on the court, and their scoring potential (Junge et al., 2000). These external factors interact with internal motivations and may lead to rapid shifts between prosocial and antisocial behaviours. In many cases, the decision to act in a prosocial way, such as assisting an opponent, may conflict with the desire to win (Junge et al., 2000). This ongoing tension between ethical conduct and competitive goals reinforces the view that fair Play is not a fixed rule, but a flexible construct shaped by both psychological and contextual influences. Several studies across different sports have also revealed behavioural differences between male and female athletes, often related to playing styles and attitudes toward rules (Junge et al., 2000; Kavussanu & Ring, 2016). For instance, female athletes are generally more likely to adhere to Fair Play principles, showing greater respect for rules and more cooperative behaviour during competition (Kavussanu & Ring, 2016; Acar et al., 2022; Bermejo et al., 2018; Forsdike & O'Sullivan, 2022; Lazarević et al., 2014; Pelegrín et al., 2013). Furthermore, a study involving 726 athletes found that female participants rated fair play as the most important aspect of sport, while male participants prioritized enjoyment (Iturbide & Elosua, 2012). These differences are often explained by gender-based social norms that develop through differentiated socialization processes from early childhood. In addition, several studies have demonstrated that fair play and disciplinary behaviour significantly affect competitive outcomes. Research in both team and individual sports indicates that unethical conduct, such as receiving cards, technical fouls, or expulsions, reduces the likelihood of success. Conversely, athletes and teams who display greater discipline and fair play often achieve better sporting results (Anwar Ali et al., 2025; Fruchart & Rulence-Pâques, 2016). For instance, a ten-year analysis of German leagues found a negative correlation between unethical behaviour and team performance (Krahé, 2025). Similarly, Badiella et al. (2022), analysing 1.826 football matches from top European leagues, observed that a player expulsion frequently led to increased goal-scoring opportunities for the opposing team, disadvantaging the penalised side. In basketball, a study of 74 athletes aged 18-25 identified an inverse correlation between aggression and sportsmanship (Kalyan, Rao, & Panda, 2023). Further studies in the NBA (Mikołajec, Maszczyk, & Zając, 2013) and the Olympic Games (Leicht, Gómez, & Woods, 2017) found that the number of fouls committed, along with other variables, was a reliable predictor of performance outcomes. In HB, recent studies confirm that the most successful teams in championships or tournaments tend to commit fewer technical fouls. Teams with higher numbers of infractions or exclusions due to unsporting conduct generally perform worse (Anwar Ali et al., 2025; Meletakos et al., 2025). These findings reinforce the idea that adherence to rules and emotional self-regulation are not only ethical imperatives but also strategic advantages in competitive sport (Meletakos et al., 2025).

Despite increasing interest in the ethical dimension of sport, empirical evidence on fair play in HB, especially concerning the relationship between fair play and performance, as well as behavioural differences between male and female athletes at the international level, remains limited. Therefore, the present study aims to examine whether fair play behaviour is associated with competitive performance, as measured by final rankings or outcomes. An additional objective is to analyse gender differences in Fair Play by comparing the behaviours of men's and women's teams participating in the HB World Championships between 2007 and 2023. The findings of this study aim to address a key gap in the literature. For professionals in sport science, federations, and governing bodies, this perspective is essential for developing effective educational and

training programmes that promote fair play, ethical awareness, emotional regulation, and social responsibility in sport.

METHODS

Participants

To analyse statistics team fair play, a total of 464 games from the nine men's World Championships (Germany, 2007; Croatia, 2009; Sweden, 2011; Spain, 2013; Qatar, 2015; France, 2017; Germany-Denmark, 2019; Egypt, 2021; Poland-Sweden, 2023) and the nine women's World Championships (France, 2007; China, 2009; Brazil, 2011; Serbia, 2013; Denmark, 2015; Germany, 2017; Japan, 2019; Spain, 2021; Denmark-Norway-Sweden, 2023) were collected.

Procedures

All the results were retrieved from the results competitions on the official website of the International Handball Federation (IHF) (<http://www.ihf.info/competitions>). All the data were collected by official statisticians of the competition who were previously trained to collect the data. Numerous studies have also used data from the same source previously (Gómez et al., 2014; Konstantinos et al., 2018; Meletakos et al., 2011; Oliveira et al., 2012; Rubia et al., 2020; Saavedra et al., 2018). The reliability of data from IHF was verified by previous important studies which tested match-related statistics of the 2005, 2007, and 2009 Men's World Championships (Meletakos et al., 2011), with a Cohen's kappa coefficient was 0.991; and the 2015 Women's World Championship (Costa et al., 2017), with Cohen's Kappa values for inter- and intra-observer reliability greater than .90 and agreement with IHF scores greater than 95%. No informed consent was necessary because the information on the website that was used in the study is in the public domain.

Measures

The following data were recorded: Blue card (BC), Disqualification with report (DR), Red cards (RC), 2-Minute Suspensions (2-Min), Yellow cards (YC). Matches played (MP), Average per game (AVG), and Total points (TP).

The average fair play score (AVG) for each team is calculated in each championship using the formula $AVG = TP/MP$, where TP represents the total fair play points earned by a team in the championship and MP stands for the number of matches played by the team in that championship. The total fair play points of each team are calculated using the following:

$$TP = (BC) \times 10 + (RC) \times 5 + (2\text{-Min}) \times 2 + (YC) \times 1$$

Therefore, the higher the fair play points, the more severe the disciplinary sanctions imposed on the team. The Fair Play Ranking (FPR) is established based on the average Fair Play (AVG) score of each team in each championship. A lower AVG for the best fair play ranking. The final ranking in the championship is determined by the final position. This variable was divided into six groups: 1st to 4th place, 5th to 8th place, 9th to 12th place, 13th to 16th place, 17th to 20th place, and 21st to 24th place. Other studies considered conducting similar groups (Almeida et al., 2020).

Data analysis

Basic statistical descriptors (mean and standard deviation) were calculated for the variables of women's and men's teams in the World Handball Championship between 2007 and 2023. The Kolmogorov-Smirnov statistical test confirmed the absence of normality. The Mann-Whitney U test was used to determine any

differences between the men's and women's teams on the variables analysed in the study. Statistical power analysis, G*Power 3.1, was used to determine the power statistical analysis and the effect size of the model. The values of this statistic were interpreted in terms of size following recommendations in the literature (Faul et al., 2009): > 0.20 small effect, > 0.50 medium effect, > 0.80 large effect. A p -value of $< .05$ was considered statistically significant. The statistical analysis was performed using the software package SPSS version 24.0 (IBM Corp., Armonk, NY, USA).

RESULTS

Table 1 presents the descriptive statistics for each study variable across men's and women's national teams participating in the World Handball Championships from 2007 to 2023. The data reflects the average values recorded by each team in each respective championship. For the variables average fair play (AVG) and fair play points (FP), men's teams consistently record higher averages than women's teams in all editions of the championship, except for 2017. Similarly, the averages for BC/DR and RC were equal to or higher among men's teams across all tournaments. Regarding 2-minute suspensions and yellow cards, the average value for men's teams also exceeded those of women's teams in every edition except for 2007. The highest average number of 2-minute suspensions and yellow cards among men's teams was observed during the 2009 World Championship with 36.67 ± 9.3 and 28.04 ± 2.11 , respectively. For women's teams, the highest average number of 2-minute suspensions was recorded during the 2019 World Championship (30.58 ± 8.38), while the highest average for yellow card suspensions was observed in the 2009 World Championship (26.83 ± 2.51).

Table 2 presents the results of the Mann-Whitney U test comparing men's and women's teams for each edition of the World HB Championship between 2007 and 2023. The values are reported as averages. Statistically significant differences between the men's and women's teams were observed in the AVG variable for all championships except for the 2017 championships. For the TP variable, significant differences were found in all editions except the 2007, 2015, and 2017 championships. The BC/DR variable showed a significant difference in the 2011 championship ($p < .01$), while RC variable showed significant differences in both the 2011 and 2013 editions ($p < .01$). Regarding 2-minute suspension, statistically significant differences were found in the 2007 and 2013 World Championships ($p < .05$), and in the 2009, 2015, 2021, and 2023 World Championships ($p < .01$). Significant differences for the YC variable were observed in the 2013 ($p < .05$) and 2019 ($p < .01$) Championship. In terms of effect sizes ($f^2 > 0.80$), large effects were observed in multiple editions of the World Championships. Specifically, a large effect was observed for 2Min ($f^2 = 0.82$) in the 2007 championship; for AVG ($f^2 = 0.88$) and 2Min ($f^2 = 0.91$) in 2009; for BC/DR ($f^2 = 1.45$) and RC ($f^2 = 1.00$) in 2011; for AVG ($f^2 = 0.97$) and RC ($f^2 = 0.85$) in 2013; for AVG ($f^2 = 1.00$) and 2Min ($f^2 = 0.91$) in 2015; for YC ($f^2 = 1.04$) in 2019; for AVG ($f^2 = 0.82$), TP ($f^2 = 0.83$), and 2Min ($f^2 = 0.84$) in 2021; and for AVG ($f^2 = 0.84$) in the 2023 championship.

Table 3 presents the descriptive statistics for each variable based on the final ranking of the men's and women's national teams at the World HB Championships held between 2007 and 2023. The data represent the average values of the teams according to their final position in the tournament standings. Among the teams ranked first, the men's teams recorded a lower average AVG (7 ± 4.77) compared to the women's teams (11 ± 6.72). Regarding 2-minute penalties, the first-ranked men's teams averaged 28.67 ± 6.94 , while the first-ranked women's teams averaged 32.44 ± 9.24 .

Table 1. Results of the fair play variables analysed in the Men's and Women's World Championships.

Year	Teams	AVG	TP	BC/DR	RC	2Min	YC	MP
		M(SD)	M(SD)	M(SD)	M(SD)	M(SD)	M(SD)	M(SD)
2007	Men	11.88(1.96)	90.88(25.46)	0	1.38(1.09)	21.42(5.22)	21.42(5.22)	7.67(1.83)
	Women	10.65(2.01)	82.13(26.32)	0	0.92(1.06)	27.17(9.43)	23.21(5.23)	7.67(1.83)
2009	Men	11.75(2.68)	103.25(30.39)	0	1.21(1.28)	36.67(9.3)	28.04(2.11)	9.17(0.38)
	Women	9.67(1.96)	88.46(17.74)	0	0.71(0.85)	29.04(7.17)	26.83(2.51)	9.17(0.38)
2011	Men	11.9(2.27)	91.96(23.14)	1.29(1.19)	1.29(1.19)	31.21(8.66)	22.67(3.27)	7.67(0.76)
	Women	10.48(1.77)	76.83(17.89)	0.04(0.2)	0.33(0.63)	26.96(7.31)	20.83(4.45)	7.33(1.27)
2013	Men	11.78(2.32)	82(17.68)	0.04(0.2)	0.92(1.1)	27.79(6.03)	21.42(3.85)	7(1.02)
	Women	9.82(1.65)	69.29(18.32)	0	0.21(0.41)	24.33(7.71)	19.58(4.22)	7(1.02)
2015	Men	13.6(2.41)	98.08(17.38)	0.04(0.2)	0.58(0.77)	36.38(6.61)	22(4.36)	7.33(1.27)
	Women	11.39(1.94)	83.96(21.52)	0.04(0.2)	0.58(0.71)	29.58(8.17)	21.46(5.22)	7.33(1.27)
2017	Men	10.2(1.66)	71.17(14.47)	0	0.63(0.71)	25.63(5.72)	16.79(4.25)	7(1.02)
	Women	10.27(2.31)	71.21(15.52)	0	0.71(0.85)	25.58(5.83)	16.5(3.76)	7(1.02)
2019	Men	10.54(2.23)	83.38(16.37)	0.04(0.2)	1.04(1.16)	32.25(6.27)	13.25(3.61)	8(1.18)
	Women	9.05(1.94)	72.88(20.45)	0	0.46(0.65)	30.58(8.38)	9.42(3.71)	8(1.18)
2021	Men	9.7(3.21)	65.16(22.18)	0.06(0.24)	1.16(1.52)	26.03(7.3)	6.69(2.91)	6.75(0.98)
	Women	7.51(1.98)	49.97(13.08)	0	0.66(0.78)	20.59(5.39)	5.5(3.09)	6.69(0.99)
2023	Men	8.67(2.01)	59.5(13.24)	0.09(0.39)	1.06(1.19)	24.5(4.18)	4.25(1.95)	7(1.24)
	Women	7.09(1.73)	49.69(14.48)	0	0.56(0.8)	21.56(6.66)	3.75(2.47)	7(1.24)
Total	Men	10.98(2.72)	81.41(24.94)	0.17(0.75)	1.03(1.16)	28.83(8.25)	16.57(8.57)	7.47(1.31)
	Women	9.39(2.37)	70.1(22.76)	0.01(0.09)	0.57(0.78)	25.81(7.99)	15.53(8.91)	7.42(1.36)

Note. AVG: Average per match; TP: Total points of fair play; BC/DR: Blue card/Disqualification with report; RC: Red Cards; 2Min: 2 Minute Suspensions, YC: Yellow cards; MP: Matches played.

Table 2. U-Mann-Whitney test results for the men's and women's teams in each championship.

Variable	2007 (n = 48)								2009 (n = 48)								2011 (n = 48)							
	Men	Women	U	Z	p	1-β	f²	Men	Women	U	Z	p	1-β	f²	Men	Women	U	Z	p	1-β	f²			
AVG	28.75	20.25	186	-2.105	.03*	0.53	0.61	30.15	18.85	152.5	-2.796	.005**	0.83	0.88	29.54	19.46	167	-2.496	.013*	0.63	0.69			
TP	27.15	21.85	224.5	-1.31	.19	0.2	0.33	29.35	19.65	171.5	-2.403	.016*	0.5	0.59	29.10	19.90	177.5	-2.279	.02*	0.67	0.73			
BC/DR	24.50	24.50	288	0	1	-	-	24.50	24.50	288	0	1	-	-	32.67	16.33	92	-4.678	.001**	0.99	1.45			
RC	27.90	21.10	206.5	-1.777	.07	0.29	0.42	27.13	21.88	225	-1.381	.16	0.32	0.45	30.50	18.50	144	-3.245	.001**	0.91	1			
2Min	20.31	28.69	187.5	-2.077	.03*	0.77	0.82	30.38	18.63	147	-2.912	.004**	0.85	0.91	28.27	20.73	197.5	-1.869	.06	0.41	0.53			
YC	21.44	27.56	214.5	-1.521	.12	0.26	0.40	28.15	20.85	200.5	-1.830	.06	0.4	0.52	27.96	21.04	205	-1.716	.08	0.34	0.47			

Variable	2013 (n = 48)								2015 (n = 48)								2017 (n = 48)							
	Men	Women	U	Z	p	1-β	f²	Men	Women	U	Z	p	1-β	f²	Men	Women	U	Z	p	1-β	f²			
AVG	30.96	18.04	133	-3.198	.001**	0.89	0.97	30.83	18.17	136	-3.135	.002**	0.91	1	24.63	24.38	285	-0.062	.95	0.05	0.03			
TP	29.71	19.29	163	-2.580	.01**	0.64	0.70	28.17	20.83	200	-1.816	.06	0.66	0.72	24.46	24.54	287	-0.021	.98	0.05	0			
BC/DR	25	24	276	-1	.31	-	-	24.50	24.50	288	0	1	0.95	1.11	24.50	24.50	288	0	1	-	-			
RC	29.92	19.08	158	-3.066	.002**	0.8	0.85	24.29	24.71	283	-0.116	.9	0.59	0.66	24.19	24.81	280.5	-0.170	.86	0.06	0.1			
2Min	28.98	20.02	180.5	-2.220	.02*	0.38	0.49	29.71	19.29	163	-2.586	.01**	0.85	0.91	24.04	24.96	277	-0.227	.82	0.05	0			
YC	28.69	20.31	187.5	-2.083	.03*	0.32	0.45	25.92	23.08	254	-.704	.48	0.06	0.11	24.96	24.04	277	-0.228	.82	0.05	0.07			

Variable	2019 (n = 48)							2021 (n = 64)							2023 (n = 64)						
	Men	Women	U	Z	p	1-β	f ²	Men	Women	U	Z	p	1-β	f ²	Men	Women	U	Z	p	1-β	f ²
AVG	28.98	20.02	180.5	-2.219	.02*	0.65	0.71	40.34	24.66	261	-3.371	.001**	0.88	0.82	39.95	25.05	273.5	-3.204	.001**	0.9	0.84
TP	28.52	20.48	191.5	-1.991	.04*	0.46	0.56	40.58	24.42	253.5	-3.473	.001**	0.89	0.83	39.92	25.08	274.5	-3.191	.001**	0.77	0.70
BC/DR	25	24	276	-1	.31	-	-	33.50	31.50	480	-1.426	.15	-	-	33.50	31.50	480	-1.425	.15	-	-
RC	27.85	21.15	207.5	-1.820	.06	0.53	0.61	34.58	30.42	445.5	-0.966	.33	0.35	0.41	36.28	28.72	391	-1.770	.07	0.47	0.49
2Min	26.29	22.71	245	-0.888	.37	0.11	0.22	40.72	24.28	249	-3.539	.001**	0.9	0.84	38.55	26.45	318.5	-2.605	.009**	0.52	0.52
YC	30.71	18.29	139	-3.092	.002**	0.93	1.04	36.34	28.66	389	-1.662	.09	0.33	0.39	35.05	29.95	430.5	-1.104	.26	0.13	0.22

Note. AVG: Average per game; TP: Total points; BC/DR: Blue card/Disqualification with report; RC: Red Cards; 2Min: 2 Minute Suspensions, YC: Yellow cards; Z: Mann-Whitney U test; *p < .0; **p < .01.

Table 3. Results based on the ranking of the Men's and Women's World Championships.

Ranking	Teams	FPR	AVG	TP	BC/DR	RC	2Min	YC	MP
		M(SD)	M(SD)	M(SD)	M(SD)	M(SD)	M(SD)	M(SD)	M(SD)
1	Men	7(4.77)	9.5(2.01)	87.67(20.71)	0	1(1)	28.67(6.94)	20(8.13)	9.22(0.66)
	Women	11(6.72)	9.35(2.6)	87.44(24.05)	0	0.33(0.7)	32.44(9.24)	20.89(9.26)	9.33(0.5)
2	Men	9.22(7.2)	9.88(2.31)	91.78(25.43)	0.11(0.33)	1(1.58)	30.67(4)	21(9.26)	9.22(0.66)
	Women	11.56(6.83)	8.87(1.48)	83.33(16.8)	0	0.44(0.72)	30.11(5.53)	20.89(9.32)	9.33(0.5)
3	Men	7.11(2.26)	9.6(1.48)	77.56(28.39)	0.11(0.33)	0.44(0.72)	31.56(5.15)	20.89(10.22)	9.22(0.66)
	Women	11(5.7)	8.91(1.61)	83.22(15.51)	0	0.22(0.44)	31.33(6.4)	19.44(9.4)	9.33(0.5)
4	Men	11.44(7.21)	10.46(2.52)	96.22(21.28)	0.11(0.33)	1.11(0.6)	33.56(7.58)	21.78(9.37)	9.22(0.66)
	Women	10.44(5.48)	9.05(2.46)	84.78(24.07)	0	0.33(0.7)	30.44(5.94)	22.22(10.26)	9.33(0.5)
5	Men	10.78(8.02)	10.51(2.88)	87.44(26.91)	0	0.89(1.05)	31.67(9.28)	19.67(8.7)	8.33(1.11)
	Women	14(6.44)	10.04(2.66)	85.11(25.8)	0	0.56(0.52)	31.89(9.95)	18.56(9.73)	8.44(1.13)
6	Men	8.44(8.17)	9.57(2.55)	79.33(21.61)	0.11(0.33)	0.22(0.44)	28.33(7.03)	19.56(9.32)	8.33(1.11)
	Women	17.89(7.39)	10.53(1.89)	89.33(22.14)	0	0.78(1.3)	33(7.87)	19.44(9.36)	8.44(1.13)
7	Men	11.11(9.26)	10.96(4.15)	90.11(32.74)	0.33(1)	1.89(1.76)	30.67(9.51)	18.89(10.54)	8.33(1.11)
	Women	17.11(7.02)	10.24(1.68)	86.78(18.25)	0	0.33(0.5)	32.44(6.32)	20.22(8.85)	8.44(1.13)
8	Men	14.89(8.17)	11.53(2.89)	98(32.73)	0.44(1.01)	1.67(1.5)	32.67(9.77)	19.22(9.02)	8.33(1.11)
	Women	10.33(7.61)	9.05(3.22)	77.56(34.47)	0	0.67(1.11)	28.22(11.61)	17.78(9.4)	8.44(1.13)
9	Men	13.44(6.4)	11.18(1.83)	79.67(20.08)	0	0.67(0.7)	28.44(7.14)	17.67(7.81)	7.11(1.36)
	Women	12.56(6.46)	9.42(2.43)	64.67(22.84)	0	0.33(0.7)	23.67(6.81)	15.67(8.61)	6.78(1.2)
10	Men	18.56(5.31)	12.61(2.16)	90.44(25.94)	0.11(0.33)	0.89(0.78)	32.11(8.66)	18(9.22)	7.11(1.36)
	Women	14.67(4.61)	10.04(2.31)	68.56(21.84)	0	0.33(0.7)	25.11(6.77)	16.67(8.27)	6.78(1.2)

11	Men	20.11(5.11)	12.96(2.34)	92.67(27.73)	0.44(1.33)	1.56(1.42)	31.22(8.99)	18.22(8.52)	7.11(1.36)
	Women	14.78(9.64)	9.71(1.63)	66.67(20.34)	0	0.56(0.72)	24.67(5.47)	14.56(9.61)	6.78(1.2)
12	Men	15.44(5.07)	11.51(2.08)	81.89(22.64)	0.33(1)	1.11(0.92)	28.11(6.17)	16.78(8.25)	7.11(1.36)
	Women	13.67(8.73)	9.57(1.69)	64.78(15.34)	0	0.56(0.72)	22.78(6.99)	16.44(7.33)	6.78(1.2)
13	Men	15.89(5.88)	11.68(2.3)	76(13.76)	0.11(0.33)	1.11(0.6)	26.78(5.76)	14.89(7.7)	6.56(1.01)
	Women	12.78(8.16)	9.47(3.33)	60.78(21.04)	0	0.22(0.66)	22.11(6.88)	15.44(7.12)	6.44(1.01)
14	Men	20.67(5.4)	13.1(1.81)	85.89(16.99)	0.22(0.66)	1.33(1.22)	30.11(8.32)	16.11(7.68)	6.56(1.01)
	Women	8.11(6.43)	8.27(1.54)	53.33(12.94)	0	0.11(0.33)	19.56(3.5)	13.67(7.29)	6.44(1.01)
15	Men	7.22(5.65)	9.48(1.44)	61.67(9.81)	0	0.22(0.66)	22.44(3.32)	15(7.01)	6.56(1.01)
	Women	19.33(5.87)	11.14(2.64)	72.56(23.22)	0.11(0.33)	0.78(0.66)	26.78(8.18)	14(8.68)	6.44(1.01)
16	Men	10.78(7.87)	10.87(3.97)	73.22(38.27)	0	0.67(1.65)	26.33(12.75)	13.89(7.99)	6.56(1.01)
	Women	12.67(11.07)	9.33(1.72)	59.56(11.29)	0	0.89(0.78)	20.78(4.02)	13.56(6.34)	6.44(1.01)
17	Men	16.22(5.51)	11.78(2.01)	82.11(22.05)	0.22(0.44)	0.89(0.78)	28.89(8.49)	16.78(7.46)	6.89(0.92)
	Women	10.78(6.94)	8.98(1.89)	62.22(16.05)	0	0.22(0.44)	23.44(5.02)	14.22(8.99)	6.89(0.92)
18	Men	14.67(5.38)	11.7(2.45)	81(20.76)	0.22(0.66)	1(0.86)	28.44(7.33)	15.89(7.88)	6.89(0.92)
	Women	14.44(9.34)	9.88(2.55)	68.44(20.36)	0	0.89(0.92)	23.67(6.65)	16.67(8.26)	6.89(0.92)
19	Men	10.67(5.07)	10.44(2.31)	73.11(23.6)	0	0.44(0.52)	27.11(9.76)	15.67(7.64)	6.89(0.92)
	Women	14.33(8.47)	10.32(3.06)	72.89(29.34)	0	0.78(0.97)	26.78(10.58)	15.44(7.84)	6.89(0.92)
20	Men	21.22(5.42)	13.47(1.91)	93.78(22.73)	0.56(1.13)	1.78(1.56)	32.56(10.74)	16.22(7.8)	6.89(0.92)
	Women	14.44(7.14)	10.06(3.23)	70.22(25.55)	0	1(1)	25.67(9.15)	13.89(8.88)	6.89(0.92)
21	Men	13(7.03)	11.21(2.1)	77.67(20.46)	0.11(0.33)	1(1)	27.89(9)	15.56(7.35)	6.89(0.92)
	Women	13(9.64)	9.45(1.89)	65.56(16.2)	0.11(0.33)	0.67(0.86)	23.67(5.17)	13.78(7.67)	6.89(0.92)
22	Men	12.78(9.75)	10.73(3.46)	74.33(26.91)	0.22(0.66)	1.11(1.05)	26.44(10.85)	15.22(8.52)	6.89(0.92)
	Women	12(10.38)	9.01(2.52)	62(18.67)	0	0.78(0.83)	22.11(7)	13.89(8.11)	6.89(0.92)
23	Men	13.11(6.67)	11.15(1.34)	77.33(15.83)	0.22(0.44)	0.89(0.6)	28.11(6)	14.67(8.45)	6.89(0.92)
	Women	14.33(6.24)	9.42(2.29)	65.33(19.58)	0	0.22(0.44)	25.11(6.95)	14(7.22)	6.89(0.92)
24	Men	11.78(8.39)	10.4(2.82)	72(21.52)	0	0.89(0.78)	25.67(7.81)	15.33(8.3)	6.89(0.92)
	Women	12.11(8.14)	9.17(2.02)	63.44(16.5)	0	1.11(0.6)	22.44(6.65)	13(8.7)	6.89(0.92)

Note. FPR: Fair Play Ranking, AVG: Average per match; TP: Total points of fair play; BC/DR: Blue card/Disqualification with report; RC: Red Cards; 2Min: 2 Minute Suspensions, YC: Yellow cards; MP: Matches played.

Table 4. U-Mann-Whitney test results for the men's and women's teams based on the final rankings of the world championships.

Variable	1 st to 4 th (n = 72)							5 th to 8 th (n = 72)						
	Men	Women	U	Z	p	1-β	f ²	Men	Women	U	Z	p	1-β	f ²
RTFP	32.14	40.86	491	-1.77	.07	0.39	0.41	31.96	41.04	484.5	-1.84	.06	0.44	0.44
AVG	40.43	32.57	506.5	-1.59	.11	0.37	0.39	38.13	34.88	589.5	-0.65	.51	0.16	0.24
TP	38.35	34.65	581.5	-0.74	.45	0.10	0.16	37.64	35.36	607	-0.46	.64	0.09	0.15
BC/DR	38.00	35.00	594	-1.75	.07	-	-	38.50	34.50	576	-2.04	.04*	-	-
RC	42.92	30.08	417	-2.93	.003**	0.76	0.65	40.44	32.56	506	-1.74	.08	0.53	0.49
2Min	36.25	36.75	639	-0.1	.91	0.05	0.004	35.40	37.60	608.5	-0.44	.65	0.05	0.06
YC	35.86	37.14	625	-0.25	.79	0.05	0.006	36.82	36.18	636.5	-0.13	.89	0.05	0.03
Variable	9 th to 12 th (n = 72)							13 th to 16 th (n = 72)						
	Men	Women	U	Z	p	1-β	f ²	Men	Women	U	Z	p	1-β	f ²
RTFP	40.68	32.32	497.5	-1.69	.08	0.44	0.44	37.01	35.99	629.5	-0.20	.83	0.05	0.05
AVG	46.74	26.26	279.5	-4.15	.001**	0.99	1.15	43.11	29.89	410	-2.68	.007**	0.75	0.64
TP	45.03	27.97	341	-3.45	.001**	0.96	0.91	42.57	30.43	429.5	-2.46	.01**	0.68	0.60
BC/DR	38.00	35.00	594	-1.75	.07	-	-	37.01	35.99	629.5	-0.60	.54	0.11	0.17
RC	43.00	30.00	414	-2.87	.004**	0.83	0.71	38.78	34.22	566	-1.03	.3	0.29	0.34
2Min	44.53	28.47	359	-3.26	.001**	0.92	0.83	42.14	30.86	445	-2.29	.02*	0.61	0.55
YC	38.71	34.29	568.5	-0.89	.37	0.15	0.22	37.99	35.01	594.5	-0.60	.54	0.07	0.11
Variable	17 th to 20 th (n = 72)							21 st to 24 th (n = 72)						
	Men	Women	U	Z	p	1-β	f ²	Men	Women	U	Z	p	1-β	f ²
RTFP	39.67	33.33	534	-1.28	.19	0.23	0.30	36.26	36.74	639.5	-0.09	.92	0.05	0.02
AVG	44.28	28.72	368	-3.15	.002**	0.91	0.80	44.22	28.78	370	-3.13	.002**	0.81	0.70
TP	42.78	30.22	422	-2.54	.01**	0.71	0.62	42.51	30.49	431.5	-2.43	.01**	0.67	0.59
BC/DR	39.00	34.00	558	-2.30	.02*	-	-	38.01	34.99	593.5	-1.39	.16	0.28	0.34
RC	39.31	33.69	547	-1.21	.22	0.24	0.31	39.69	33.31	533	-1.39	.16	0.29	0.35
2Min	41.57	31.43	465.5	-2.05	.04*	0.55	0.51	41.51	31.49	467.5	-2.03	.04*	0.53	0.50
YC	37.93	35.07	596.5	-0.581	.56	0.08	0.13	38.83	34.17	564	-0.94	.34	0.12	0.19

Note. RTFP: Rank Team Fair Play; AVG: Average per game; TP: Total points; BC/DR: Blue card/Disqualification with report; RC: Red Cards; 2Min: 2 Minute Suspensions, YC: Yellow cards; z: Mann-Whitney U test; *p < .05; **p < .01.

Table 4 presents the results of the Mann-Whitney U test comparing men's and women's teams across different final ranking groups. Values are reported as group means. Statistically significant differences were observed between men's and women's teams ranked 1st to 4th in RC ($p < .01$, $f^2 = 0.65$). Among teams ranked 5th to 8th, significant differences were found in BC/DR ($p < .05$, $f^2 < 0.50$). For the teams ranked 9th to 12th, statistically significant differences were observed in multiple variables: AVG ($f^2 = 1.15$), TP ($f^2 = 0.91$), RC ($f^2 = 0.71$), and 2-minute suspensions ($f^2 = 0.83$). In the 13th to 16th place group, significant differences were found in AVG ($f^2 = 0.64$), TP ($p < .01$, $f^2 = 0.60$), and 2Min ($p < .05$, $f^2 = 0.55$). Among teams ranked 17th to 20th, significant differences emerged in AVG ($f^2 = 0.80$), TP ($p < .01$, $f^2 = 0.62$), as well as in BC/DR and 2Min ($p < .05$, $f^2 = 0.51$). Finally, for the teams ranked 21st to 24th, statistically significant differences were found in AVG ($f^2 = 0.70$), TP ($p < .01$, $f^2 = 0.59$), and 2Min ($p < .05$, $f^2 = 0.50$).

DISCUSSION

The present study aimed to examine the relationship between fair play behaviour and athletic performance, as reflected in final competition rankings, and to explore potential gender differences in fair play among national teams participating in the HB World Championship from 2007 to 2023. Regarding the first objective, the findings indicate that teams achieving higher final rankings generally demonstrated more disciplined conduct. In contrast, lower and mid-ranked teams exhibit higher levels of undisciplined behaviour. This pattern could be attributed to reduced experience or limited capacity for emotional regulation and stress management, which are more prevalent among less successful teams. These results support the idea that fair play is positively associated with athletic performance, reinforcing the notion that ethical and disciplined behaviour is compatible with competitive success. Cultural incidents should also be considered when interpreting behavioural patterns in sport. Cultural dimensions such as individualism, performance orientation, and long-term planning may shape athletes' training practices, competitive behaviours, and emotional responses in high-pressure scenarios (Sava et al., 2024). The present results are consistent with existing literature indicating that athletic success is not necessarily linked to frequent rule violations or excessively aggressive play, but rather to offensive technical-tactical proficiency, team cohesion, and emotional control (Milanović et al., 2018; Bilge, 2012). This aligns with the systematic review by Ferrari et al. (2019) which showed that the most of match analysis research focuses on offensive metrics, goalkeeping performance, and pace of play, while disciplinary with less attention given to disciplinary behaviour. Collectively, these findings highlight the importance of viewing fair play not merely as compliance with rules or the absence of penalties, but as a broader indicator of athletes' personal and moral development. Coaching strategies, team culture, and educational interventions play a vital role in promoting prosocial behaviour and respectful competition (Granero-Gallegos et al., 2017). In addressing the second objective, the study found statistically significant gender differences in fair play indicators. Male teams consistently record higher average values across disciplinary variables such as AVG, TP, BC/DR, RC, and 2-minute suspensions. These findings suggest a tendency towards a more physically intense and less regulated style of play in men's competitions. Prior research supports this observation, indicating that male athletes often adopt more confrontational defensive strategies (Fasold & Redlich, 2018). Interestingly, some penalised physical actions, such as "legal stops" in HB, can function as tactical components rather than violations of ethical conduct. Therefore, a moderate level of strategically applied physicality may contribute to team performance. This perspective is supported by Laxdal and Ivarsson (2023), who found a positive association between 2-minute suspensions and match victories in men's HB, a pattern not observed in women's competitions. The statistically significant differences observed via the Mann-Whitney U test, together with large effect sizes, indicate that men and women exhibit distinct approaches to competitive behaviour. These differences may be attributed to a combination of biological (Hunter et al., 2023), cultural (Capranica et al., 2013), and

psychological factors (Kew et al., 2024) that influence playing style, emotional regulation, and risk-tactical decision.

In line with previous findings in other team sports (Petrie et al., 2024; Taketomi et al., 2021), the current results affirm that gender is a relevant factor in shaping disciplinary conduct and competitive behaviour. Male athletes appear more inclined to employ physical, high-intensity strategies, which often result in increased penalisation. Female athletes, by contrast, tend to show greater adherence to rules and are less frequently involved in sanctionable actions. However, certain exceptions emerged, such as during the 2019 Women's World Championship, an unusually high average number of 2-minute suspensions was recorded (30.58 ± 8.38). This suggests that contextual variables such as match intensity or refereeing style may influence behavioural outcomes. One plausible explanation for the observed gender-based differences involves an underlying psychological mechanism. Research suggests that women typically exhibit higher levels of empathic concern and sensitivity to others' emotions (Kavussanu et al., 2009; Cotterill et al., 2020), which may influence their behavioural responses during competition. In contrast, male athletes may be more susceptible to performance pressure and external evaluation, leading to a more aggressive approach and increasing the incidence of disciplinary infractions (Im et al., 2018). These results support the interpretation of Fair Play as a situationally driven construct, rather than a fixed trait, subject to variations based on game context, match significance, and emotional arousal.

It is also important to account for the potential influence of refereeing decisions on gender differences. For example, Souchon et al. (2013), in a study of 145 male referees, found that female players were judged more strictly, despite committing fewer infractions, indicating the possible presence of unconscious gender bias. However, the results of the present study suggest the opposite: male athletes were sanctioned more frequently, suggesting that the intensity and style of their play had a stronger effect on referee decisions than any potential bias.

Similarly, Pic (2017) conducted an observational analysis of matches from the 2012 Olympic Games and found that men's and women's teams adopted different tactical approaches. Female teams were observed to use more cooperative offensive strategies and to engage in less physical contact, which may reduce the likelihood of disciplinary sanctions. These differences in technical and tactical patterns may help explain the lower TP values recorded in the women's competitions.

Strengths and limitations

One of the main strengths of this study is its focus on gender differences in HB, an area that has received limited attention in the scientific literature. This research contributes valuable empirical evidence on the relationship between gender and fair play in high-level competition contexts, specifically within international HB. Another notable strength is the extended data collection period (2007–2023), which allowed the inclusion of multiple editions of the HB World Championships, enhancing the representativeness and reliability of the results. However, the study presents several limitations. First, it is based exclusively on quantitative data obtained from historical records, without considering the specific context of the game, such as the type of match, the Championship phase, the opponents' characteristics, the nature of the foul, or the player's specific role and position on the court. This restricts the ability to interpret the behaviours observed and to explore situational influences on fair play conduct. Second, the absence of athletes' subjective perspectives and lived experiences limits the depth of the analysis. Third, the potential impact of non-sporting factors, such as variations in refereeing standards between men's and women's competitions, was not examined and may have influenced the results.

Practical applications

The findings of this study provide practical guidance for coaches, sport psychologists, and mental coach, facilitating the promotion of fair play and the enhancement of emotional regulation in high-pressure competitive contexts. Interventions aimed at improving athletes' emotional self-regulation, such as mindfulness training and simulated match scenarios, may contribute to a reduction in red cards and suspensions. Conflict management and the promotion of fair play can be enhanced through post-match feedback sessions and structured reflections, fostering team cohesion and prosocial behaviour. Observed gender differences indicate the need for targeted interventions: in men's teams, efforts should focus on reducing antisocial behaviour and promoting empathy, whereas in women's teams, emphasis should be placed on reinforcing prosocial behaviour and collaborative offensive strategies. Coaches and referees play a critical role in ensuring fairness and consistency in disciplinary decisions, thereby supporting a respectful and sustainable sporting culture.

CONCLUSION

Regarding the first objective, the results did not reveal a consistent relationship between fair play behaviour and final competition ranking, suggesting that a team's level of discipline or frequency of in-game penalties does not necessarily predict placement in the standings. In relation to the second objective, significant gender differences in fair play conduct were observed. Specifically, men's teams accumulated a higher number of penalties across the World Championships analysed, indicating a tendency toward more frequent rule violations compared to women's teams. These findings highlight that fair play is context-dependent and support the need for gender-sensitive interventions in coaching and mental training.

AUTHOR CONTRIBUTIONS

Iván González-García: conceptualization, methodology, data collection, formal analysis, writing - original draft. Ignazio Leale: writing - original draft, visualization. Giuseppe Battaglia: writing - review & editing. Manuel Gómez-López: conceptualization, methodology, writing - original draft, supervision.

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Effects of combined aerobic and resistance training compared to aerobic training alone on physical fitness and cognitive function in overweight and obese older adults: A randomized controlled trial

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ABSTRACT

The problem of obesity among older adults is becoming increasingly serious, leading to declines in physical fitness and cognitive function. While aerobic exercise (AE) is widely recommended for improving cardiometabolic health, combining it with resistance training (CARE) may yield broader functional benefits. This study aimed to evaluate and contrast the impacts of AE and CARE interventions on physical fitness and cognitive performance among older adults with overweight or obesity. A 12-week randomised controlled trial was conducted involving 46 overweight and obese older adults. Participants were randomized to aerobic exercise (AE) or AE + resistance training (CARE). Outcomes included body composition, senior fitness, and neuropsychological assessments. Both improved, with distinct effects: AE yielded greater reductions in weight, BMI, fat mass, and waist-hip ratio; CARE increased skeletal muscle mass, had larger strength gains, and showed greater improvements in Mini-Mental State Examination and memory tasks. Both benefit physical and cognitive outcomes in obese older adults. AE is particularly effective for fat reduction, while CARE confers additional advantages in muscle preservation, strength, and cognition. CARE may therefore represent a more comprehensive intervention to enhance health aging and maintain daily independence in this population.

Keywords: Sport medicine, Combined training, Aerobic exercise, Physical fitness, Cognitive function, Older adults with obesity.

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INTRODUCTION

Globally, rates of overweight and obesity among older adults have been steadily increasing. In the last thirty years, the obesity rate among adults has more than doubled (World Health Organization, 2024), making it a significant public health issue. This rising trend is particularly concerning, as obesity in older adults substantially elevates the risk of chronic conditions, including cardiovascular disease, type 2 diabetes, metabolic syndrome, and certain cancers (Caterson et al., 2004; Smith et al., 2005). These comorbidities contribute significantly to morbidity and healthcare burden in aging populations. From a physical fitness perspective, obesity exacerbates age-related declines in mobility, muscular strength, and endurance (Cortes et al., 2025; Zamboni et al., 2008). It accelerates the progression of sarcopenia, impairs balance, and increases the risk of falls, thereby threatening physical independence (Cruz-Jentoft et al., 2019). Finally, from a cognitive perspective, obesity can adversely affect the central nervous system and further affect cognitive domains such as executive function, memory and learning ability (Deng et al., 2025). Therefore, overweight and obesity diminish the quality of life in older adults and raise the risk of frailty, disability, and institutionalisation.

Physical exercise is widely acknowledged as a non-drug strategy for combating aging and obesity. Among various exercise modalities, aerobic exercise (AE) has received extensive attention because it can enhance physical fitness, cardiovascular health, lipid metabolism, as well as cognitive functions such as memory and attention (Bai et al., 2022; Hu et al., 2024). However, AE alone may be insufficient to address the multifaceted challenges encountered by older adults with obesity, including deficits in muscle strength, balance capacity, and executive function. In contrast, resistance training (RE) has demonstrated superior efficacy in improving muscular strength, power, and glucose metabolism (Andersson et al., 2017). Recently, researchers have begun investigating combined aerobic and resistance exercise (CARE) approaches, hypothesising that such integrated regimens may yield superior benefits across both physiological and cognitive domains.

Multiple studies have demonstrated that CARE yields greater improvements than single-modality programs in health outcomes in older adults. Firstly, compared with AE and anaerobic exercise, aerobic exercise combined with anaerobic exercise can improve cardiovascular indicators in the elderly more effectively, and reduce inflammation markers (Marzolini et al., 2012; Ihalainen et al., 2018). Secondly, from a physical performance perspective, CARE significantly enhances functional mobility, muscular strength, and overall physical capacity (Bai et al., 2022; Burich et al., 2015]. Thirdly, from a cognitive perspective, CARE may promote brain health by improving cerebral perfusion, lowering inflammatory responses, and stimulating the release of neurotrophic molecules such as brain-derived neurotrophic factor (BDNF), which play key roles in neural plasticity, neurogenesis, and overall cognition (Marinus et al., 2019; Cefis et al., 2023). However, although evidence on CARE has grown, few trials have directly contrasted its effects with AE in terms of physical performance and cognitive health among obese older adults.

Considering the rapid decline in physical and cognitive ability among overweight and obese older adults, this study compared the effects of a 12-week CARE program with AE alone. By focusing on this high-risk population, the research fills a key gap and provides evidence for developing personalised exercise intervention programs to promote healthy aging and overall well-being.

MATERIALS AND METHODS

Research design

This research employed a randomised controlled trial conducted at the community fitness centre of Xiangshuwan Community in Weifang, Shandong Province, China. Participants were recruited between October 2024 and January 2025 through posted announcements at local senior activity centres and residential bulletin boards. After completing baseline assessments and providing written informed consent,

eligible individuals were randomly allocated to either the CARE or AE group. Randomisation was computer-generated, and allocations were concealed in numbered, sealed envelopes by independent researchers not involved in other study procedures.

All exercise sessions were carried out over a 12-week intervention period and were fully supervised by certified instructors at the community gym. Outcome measurements were performed by assessors blinded to group assignments. To ensure blinding integrity, assessors were: (1) not involved in intervention delivery, (2) physically separated from training sessions, and (3) provided with anonymised participant IDs during testing. Primary outcome measures included physical fitness and cognitive function, assessed both at baseline and post-intervention (12 weeks). To minimise external confounding factors and ensure comparability between groups, all participants were instructed to maintain their habitual diet and lifestyle throughout the intervention period and to avoid additional exercise during the trial. The protocol was approved by the Ethics Committee of Zhucheng People's Hospital (Approval No. 2025CY007).

Figure 1 shows the flowchart of the participants. Among the 78 subjects who passed the screening, 28 were excluded for not meeting the criteria ($n = 15$), refusing to participate ($n = 8$), or for other reasons ($n = 5$). Fifty eligible participants were randomised equally into the CARE group ($n = 25$) or the AE group ($n = 25$). During the 12-week intervention, 1 participant in the CARE group and 3 in the AE group were lost to follow-up or discontinued the intervention. Final analyses included 24 participants in the CARE group and 22 in the AE group.

Figure 1 shows the flowchart of the test participants. Among the 78 subjects who passed the screening, 28 were excluded for not meeting the criteria ($n = 15$), refusing to participate ($n = 8$), or for other reasons ($n = 5$). Ultimately, 50 qualified subjects were randomly and equally assigned to the CARE group ($n = 25$) and the AE group ($n = 25$). During the 12-week intervention period, one subject in the CARE group and three subjects in the AE group withdrew halfway. Ultimately, the CARE group retained 24 subjects, while the AE group retained 22 subjects.

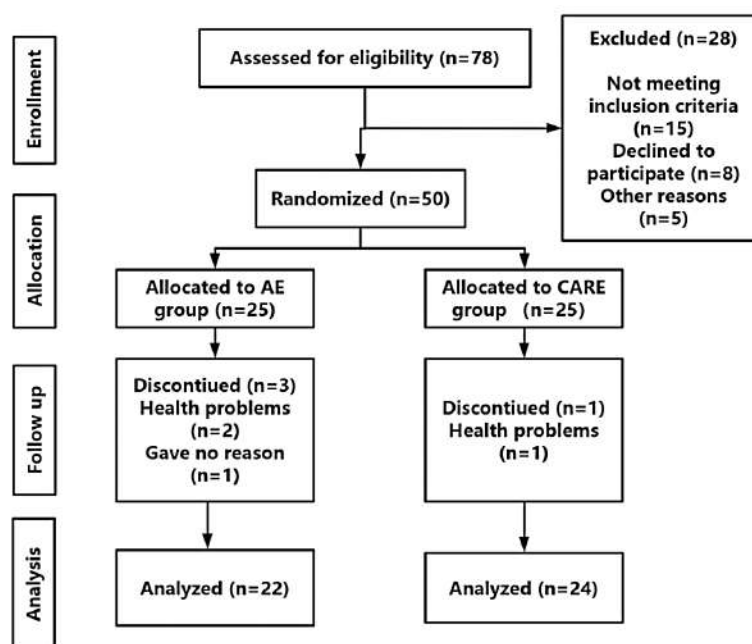


Figure 1. Participant flow diagram

Participants

Inclusion criteria for participants were as follows: Aged 60–74 years; body mass index (BMI) ≥ 24 kg/m², based on the diagnostic criteria for overweight and obesity in Chinese adults (Chen et al., 2023); no regular participation in exercise interventions within the past six months; and adequate cognitive and physical function to independently complete the training tasks. Exclusion criteria included any severe cardiovascular disease, neurological disorders, or musculoskeletal and joint conditions that could impair exercise performance. All subjects who met the inclusion criteria were randomly assigned to the CARE group or the AE group after signing written informed consent.

Sample size calculations were conducted in G*Power 3.1. Using a repeated-measures ANOVA with interaction effects, the study parameters were defined as follows: effect size $f = 0.25$, significance level $\alpha = .05$, statistical power $(1-\beta) = 0.90$, groups = 2 (CARE vs. AE), measurement points = 2 (baseline and week 12), and an assumed correlation among repeated measures of 0.5. The calculation shows that a minimum of 46 participants was needed. To maintain adequate statistical power and account for potential attrition, a total of 50 participants were planned for recruitment.

To minimise the influence of non-exercise-related factors on study outcomes, all participants were asked to keep their usual dietary patterns and daily routines during the intervention period and to avoid additional lifestyle or other exercise programs. To further account for lifestyle-related confounding effects, baseline dietary intake and physical activity were also assessed.

Intervention programme

Each formal training session was preceded and followed by a 10-minute warm-up and a 10-minute post-exercise relaxation, including both dynamic and static stretching exercises, all supervised by certified fitness instructors.

Participants in the CARE group attended three training sessions every Monday, Wednesday and Friday. Each session began with 30 minutes of moderate-intensity AE performed on a motorised treadmill (Johnson Fitness, USA). According to the definition of the American College of Sports Medicine (ACSM) (Garber et al., 2011), by separately adjusting the speed and slope of the treadmill, an exercise intensity equivalent to 64–76% of the subject's maximum heart rate (HR_{max}) can be achieved and maintained. HR_{max} was estimated using the equation $HR_{max} = 220 - \text{age}$, and heart rate was continuously monitored via a Polar H10 heart rate monitor (Polar Electro, Finland). In addition, participants' heart rates were recorded at the beginning, midpoint, and end of each aerobic session to ensure that they stayed within the target zone.

Immediately after AE, participants performed moderate-intensity resistance training at 50–69% of their one-repetition maximum (1RM), determined according to ACSM guidelines (Pollock et al., 1998). The resistance training component was machine- and dumbbell-based and targeted major upper body, core, and lower body muscle groups. Exercises were organised into two alternating routines: on Mondays and Fridays, participants performed Dumbbell Half Squat, Dumbbell Front Raise, Bent-Over Dumbbell Row, Dumbbell Shoulder Press, Dumbbell Bicep Curl, and Dumbbell Fly; on Wednesdays, Seated Chest Press, Lat Pulldown, Seated Row, Dumbbell Lunge, Seated Leg Curl, and Back Extension. Each exercise was performed in 3 sets, with 12 to 15 repetitions in each set. There was a 60–90 second break between sets, totalling approximately 20 minutes of resistance training. Training loads were progressively increased by 2–5% once participants could complete the upper limit of repetitions (15 reps) in all sets with correct form.

Participants in the AE group performed only the aerobic component at the same frequency (three times per week) and intensity (64–76% HRmax) as the CARE group. Each AE session lasted 50 minutes, with treadmill speed and incline adjusted to maintain the target heart rate, and heart rate continuously monitored in the same manner as in the CARE group.

Physical fitness outcome measures

This study employed the Senior Fitness Test (SFT) as the primary assessment tool for evaluating physical fitness. The SFT, developed by Rikli and Jones (1999), is widely applied in the elderly population and has demonstrated strong content, construct, and discriminative validity, as well as high reliability and test-retest consistency across numerous studies (Hesseberg et al., 2015). Moreover, it is also regarded as a practical, easy-to-manage and highly secure detection method, suitable for assessing the functional health of the elderly (Bhattacharya et al., 2016). Guided by this approach, the present study assessed five core aspects of physical fitness, namely body composition, muscular strength, flexibility, agility with dynamic balance, and aerobic endurance, through a series of validated, evidence-supported tests conducted at the start and end of the 12-week program.

Body composition was measured using the InBody 270 bioelectrical impedance analyser, which is highly consistent with dual-energy X-ray absorptiometry and is widely used in clinical and sports science research (Czartoryski et al., 2020). Indicators obtained included weight, BMI, skeletal muscle mass (SMM), body fat mass (BFM), body fat percentage (BFP), and waist-to-hip ratio (WHR). Muscular strength was tested through three methods: the 30-second chair stand (30s CS) for lower-limb strength, the 30-second arm curl (30s AC) for upper-limb strength, and grip strength (GS) using a CAMRY EH101 digital dynamometer with established reliability (Sánchez-Aranda et al., 2024). Flexibility was measured with the sit-and-reach test (SR) and the back scratch test (BS). Agility and balance were evaluated by the 2.4-meter up-and-go (2.4m UG) and the single-leg stance (SLS). Finally, aerobic endurance was evaluated using the 2-minute step test (2-min ST), a practical tool for estimating cardiorespiratory fitness in this population.

In summary, the assessment framework provided a comprehensive, well-structured approach for evaluating the multidimensional impact of exercise interventions on the physical fitness of older adults with obesity.

Cognitive function outcome measures

Cognitive function is typically divided into several core areas, including global cognition, memory, attention, language, executive function, visuomotor coordination, and processing speed (Harvey, 2019). To comprehensively assess these domains, this study employed a battery of validated cognitive tests.

Cognitive function was assessed using the Mini-Mental State Examination (MMSE), a commonly adopted screening instrument for older adults that is concise, straightforward to administer, and supported by strong evidence of reliability and validity (Baek et al., 2006). To further measure attention and memory, the Digit Span Test (DST) was applied, including the forward sequence (DST-F), which reflects immediate attentional capacity, and the backward sequence (DST-B), which evaluates working memory and the ability to mentally manipulate information (Ostrosky-Solís & Lozano, 2006).

Executive function was examined through the Trail Making Test (TMT), including Part A (TMT-A) and Part B (TMT-B), which also capture participants' processing speed, cognitive flexibility, and task-switching capabilities (Cangoz et al., 2009). Additionally, the Simple Reaction Time Test (SRT) measured participants' response speed, while the Grooved Pegboard Test (GPT) evaluated visuomotor coordination and fine motor

skills—key parameters for assessing hand-eye coordination in neuropsychological evaluation (Johnson et al., 1985, Heintz Walters et al., 2021).

Overall, the cognitive assessment tools employed in this study demonstrated high reliability, validity, and feasibility, proving particularly suitable for evaluating overweight and obese older adults both before and after interventions.

Statistical analysis

Data analysis was performed with IBM SPSS Statistics 26.0. A per-protocol framework was applied, retaining participants who fulfilled the assessment schedule and attended at least 80% of sessions, without substitution for missing cases.

First, to evaluate the changes within the group before and after the intervention, we first used the Shapiro Wilke test to conduct a normality test on the continuous variables. For the data that conform to the assumption of normal distribution, paired-sample t-tests assessed within-group differences. When data violated normality assumptions, non-parametric tests such as the Wilcoxon signed-rank test were adopted.

Second, to compare post-intervention outcomes between groups, this study employed covariance analysis (ANCOVA) and adjusted the baseline measurements to control for their potential impact. ANCOVA was performed only if its underlying assumptions were met, including a linear relationship between the covariate and the dependent variable, homogeneity of regression slopes, and equivalence of covariate distribution across groups. If these assumptions were not satisfied, a difference score approach (post-test minus pre-test) was adopted, and between-group differences were analysed using the Mann–Whitney U test. All tests were two-tailed, with significance defined as $p < .05$.

RESULTS

Baseline characteristics

Table 1 illustrates the baseline characteristics. Participants in the AE group and the CARE group demonstrated comparable values across all demographic, physical, and cognitive variables. The AE group had a mean age of 66.36 ± 4.46 years, compared with 65.54 ± 4.37 years in the CARE group. Height and weight were similar between groups. Measures of body composition, including BMI, SMM, BFM, BFP, and WHR, showed no notable differences. Performance on physical fitness assessments such as the 30s CS, 30s AC, GS, SR, BS, 2.4m UG, SLS, and 2-minute ST were broadly comparable between the two groups. Baseline cognitive function, as assessed by the MMSE, DST-F, DST-B, GPT, SRT, TMT-A and TMT-B, also showed no observable group differences.

Physical fitness

Effects of aerobic exercise and combined aerobic and resistance exercise on body composition

Significant within-group improvements were found in both the AE and CARE groups after the intervention. In the AE group, weight, BMI, BFM, BFP, SMM, and WHR all showed significant reductions following the intervention ($p < .05$). In the CARE group, weight, BMI, BFM, BFP, and WHR significantly decreased post-intervention, while SMM increased ($p < .05$), as shown in Table 2.

Both groups showed marked enhancements in body composition post-intervention. Weight and BMI showed no significant differences between groups, and effect sizes were small, indicating similar outcomes. However, CARE training significantly increased skeletal muscle mass compared to AE ($p < .001$, $ES = 0.257$), whereas

AE produced greater reductions in body fat mass ($p = .035$, $ES = 0.311$) and waist-hip ratio ($p = .001$, $ES = 0.218$). Body fat percentage decreased markedly in both groups without a notable between-group difference. Overall, AE was more effective for fat reduction, while CARE was superior in preserving and increasing muscle mass.

Table 1. The characteristics of the study subjects at baseline.

Test item	AE group, n = 22	CARE group, n = 24	p-value
Age	66.36 ± 4.46	65.54 ± 4.37	.51
Height	164.66 ± 6.33	163.23 ± 8.23	.52
Weight	72.81 ± 7.57	71.51 ± 9.26	.606
BMI	26.83 ± 2.52	26.67 ± 1.5	.794
SMM	25.41 ± 3.8	24.58 ± 5.05	.531
BFM	25.81 ± 5.98	25.85 ± 3.3	.975
BFP	35.36 ± 6.03	36.44 ± 4.48	.491
WHR	0.97 ± 0.06	0.96 ± 0.05	.748
30s CS	19.59 ± 4.07	19.54 ± 5.98	.974
30s AC	25.05 ± 5.28	25.83 ± 3.61	.555
GS	30.23 ± 7.86	30.5 ± 8.76	.912
SR	8.47 ± 8.83	2.83 ± 10.9	.061
BS	-22.1 ± 11.61	-19 ± 12.97	.279
2.4m UG	5.78 ± 0.61	6.02 ± 0.72	.233
SLS	4.01 ± 2.68	3.77 ± 2.5	.753
2-min ST	97.91 ± 10.74	95.5 ± 11.63	.471
MMSE	26.86 ± 2.73	26.21 ± 2.89	.434
DST-B	3.84 ± 0.67	3.5 ± 0.78	.145
DST-F	7.59 ± 1.84	7.58 ± 1.93	.989
GPT	74.04 ± 7.06	74.95 ± 4.71	.614
SRT	520.59 ± 96.66	556.13 ± 127.52	.296
TMT-A	61.94 ± 26.51	61.5 ± 14.67	.946
TMT-B	93.61 ± 18.96	96.04 ± 20.4	.687

Note: Values are presented as mean ± standard error (SE). The following abbreviations are used throughout the text and tables: BMI = body mass index; SMM = skeletal muscle mass; BFM = body fat mass; BFP = body fat percentage; WHR = waist-hip ratio; 30s CS = 30-second chair stand test; 30s AC = 30-second arm curl test; GS = grip strength; SR = sit-and-reach test; BS = back scratch test; 2.4m UG = 2.4-meter up-and-go test; SLS = single-leg stance; 2-min ST = 2-minute step test; MMSE = Mini-Mental State Examination; DST-F = forward digit span test; DST-B = backward digit span test; GPT = grooved pegboard test; SRT = simple reaction time; TMT-A and TMT-B = Trail Making Test Part A and B. The p value for the inter-group comparison of baseline data between the AE and CARE.

Table 2. Effects of aerobic exercise and aerobic resistance training on body composition.

Test item	AE group, n = 22			CARE group, n = 24			Between-group	
	Pre-test	Post-test	p-value	Pre-test	Post-test	p-value	p-value	ES
Weight	72.81 ± 7.57	70.12 ± 7.17	< .001*	71.51 ± 9.26	70.16 ± 9.29	< .001*	.817	0.034
BMI	26.83 ± 2.52	25.87 ± 2.34	< .001*	26.67 ± 1.5	26.21 ± 1.58	< .001*	.248	0.17
SMM	25.41 ± 3.8	25.22 ± 3.72	.012**	24.58 ± 5.05	25.19 ± 5.21	< .001*	< .001#	0.257
BFM	25.81 ± 5.98	23.51 ± 5.69	< .001*	25.85 ± 3.3	24.8 ± 3.88	< .001*	.035#	0.311
BFP	35.36 ± 6.03	33.66 ± 6.38	< .001*	36.44 ± 4.48	35.6 ± 4.9	.011**	.104	0.24
WHR	0.97 ± 0.06	0.93 ± 0.06	< .001*	0.96 ± 0.05	0.95 ± 0.06	.065	.001#	0.218

Note: Values are presented as mean ± standard error (SE) unless otherwise indicated. *: significant intra-group difference ($p < .01$); **: $p < .05$. #: significant between-group difference ($p < .05$, CARE vs. AE). ES = effect size. Abbreviations: BMI = body mass index; SMM = skeletal muscle mass; BFM = body fat mass; BFP = body fat percentage; WHR = waist-hip ratio.

Effects of aerobic exercise and combined aerobic and resistance exercise on senior fitness test performance
Following the intervention, the AE group demonstrated notable improvements ($p < .05$) in the 30s CS, SR, BS, 2.4m UG, SLS, and 2-minute ST. Similarly, the CARE group exhibited significant post-intervention gains ($p < .05$) in the 30s CS, 30s AC, GS, SR, 2.4m UG, SLS, and 2-minute ST.

After the intervention, both groups improved across most Senior Fitness Test items. A notable between-group difference was observed only in the 30s arm curl test, where CARE showed greater gains than AE ($p = .001$, $ES = 0.235$). CARE also demonstrated a moderate effect in the sit-and-reach test ($ES = 0.271$), suggesting an advantage in flexibility improvement. For other measures—including chair stand, grip strength, back scratch, up-and-go, single-leg stance, and 2-minute step—both groups improved significantly within groups, while between-group differences were nonsignificant, and effect sizes were small. Overall, CARE was more effective in enhancing upper limb strength and flexibility, while both interventions yielded comparable benefits in other fitness domains. These results are detailed in Table 3.

Table 3. Effects of aerobic exercise and aerobic resistance training on Senior Fitness Test.

Test item	AE group, n = 22			CARE group, n = 24			Between-group	
	Pre-test	Post-test	p-value	Pre-test	Post-test	p-value	p-value	ES
30s CS	19.59 ± 4.07	21.95 ± 4.43	.009**	19.54 ± 5.98	23.79 ± 4.75	.002**	.184	0.041
30s AC	25.05 ± 5.28	25.82 ± 4.07	.916	25.83 ± 3.61	29.83 ± 3.55	< .001*	.001#	0.235
GS	30.23 ± 7.86	30.94 ± 7.11	.107	30.5 ± 8.76	32.83 ± 8.22	.001**	.488	0.102
SR	8.47 ± 8.83	20.26 ± 14.14	.001**	2.83 ± 10.9	12.23 ± 9.74	.001**	.066	0.271
BS	-22.1 ± 11.61	-19.1 ± 14.63	.006**	-19 ± 12.97	-15.47 ± 15.28	.059	.995	< 0.001
2.4m UG	5.78 ± 0.61	5.23 ± 0.91	.001**	6.02 ± 0.72	5.13 ± 0.59	< .001*	.904	0.018
SLS	4.01 ± 2.68	6.2 ± 2.74	< .001*	3.77 ± 2.5	8 ± 8.44	.002**	1	< 0.001
2-min ST	97.91 ± 10.74	116.64 ± 13.57	< .001*	95.5 ± 11.63	111.38 ± 10.41	< .001*	.211	0.036

Note: Values are presented as mean ± standard error (SE) unless otherwise indicated. *: significant intra-group difference ($p < .01$); **: $p < .05$. #: significant between-group difference ($p < .05$, CARE vs. AE). ES = effect size. Abbreviations: 30s CS = 30-second chair stand test, number of repetitions; 30s AC = 30-second arm curl test, number of repetitions; GS = grip strength, measured in kilograms; SR = sit-and-reach test, measured in centimetres, higher score indicates better flexibility; BS = back scratch test, measured in centimetres, higher score indicates better shoulder flexibility; 2.4m UG = 2.4-meter up-and-go test, measured in seconds, lower score indicates better mobility; SLS = single-leg stance, measured in seconds, higher score indicates better balance; 2-min ST = 2-minute step test, number of steps completed.

Table 4. Effects of aerobic exercise and aerobic resistance training on cognitive function.

Test item	AE group, n = 22			CARE group, n = 24			Between-group	
	Pre-test	Post-test	p-value	Pre-test	Post-test	p-value	p-value	ES
MMSE	26.86 ± 2.73	28.23 ± 2.14	.002**	26.21 ± 2.89	28.67 ± 1.86	< .001*	.48	0.104
DST-B	3.84 ± 0.67	4.73 ± 0.99	.003**	3.5 ± 0.78	4.88 ± 1.15	< .001*	.62	0.073
DST-F	7.59 ± 1.84	8.14 ± 1.75	.151	7.58 ± 1.93	8.67 ± 1.76	.006**	.255	0.168
GPT	74.04 ± 7.06	72.62 ± 7.02	.004**	74.95 ± 4.71	72.74 ± 4.68	< .001*	.142	0.049
SRT	520.59 ± 96.66	443.23 ± 91.58	.001**	556.13 ± 127.52	457 ± 101.52	< .001*	.613	0.075
TMT-A	61.94 ± 26.51	57.89 ± 22.46	.046**	61.5 ± 14.67	57.7 ± 13.69	.002**	.952	< 0.001
TMT-B	93.61 ± 18.96	91.1 ± 19.67	.041**	96.04 ± 20.4	95.49 ± 18.79	.762	.312	0.024

Note: Values are presented as mean ± standard error (SE) unless otherwise indicated. *: significant intra-group difference ($p < .01$); **: $p < .05$. #: significant between-group difference ($p < .05$, CARE vs. AE). ES = effect size. Abbreviations: MMSE = Mini-Mental State Examination, score range 0–30, higher score indicates better global cognition; DST-F = forward digit span test, score range 0–9; DST-B = backward digit span test, score range 0–9; GPT = grooved pegboard test, time in seconds, lower score indicates better fine motor control; SRT = simple reaction time, measured in milliseconds, lower score indicates faster response; TMT-A and TMT-B = Trail Making Tests A and B, measured in seconds, lower score indicates better executive function and task-switching ability.

Effects of aerobic exercise and combined aerobic and resistance exercise on cognitive function

Following the intervention, the AE group demonstrated notable gains ($p < .05$) in the MMSE, DST-B, GPT, SRT, and TMT-A and TMT-B, whereas DST-F showed no measurable change. Similarly, the CARE group showed marked enhancements ($p < .05$) in MMSE, DST-B, DST-F, GPT, SRT, and TMT-A, while no significant change was found in TMT-B.

Both AE and CARE groups showed improvements in most cognitive tests after the intervention. CARE had slightly greater gains in DST-B and DST-F, with small to moderate effect sizes ($ES = 0.073$ – 0.168), indicating modest advantages in working and short-term memory. Other measures—including MMSE, grooved

pegboard test, simple reaction time, and Trail Making Tests A and B—showed similar improvements between groups, with negligible effect sizes. Overall, CARE training offered slight benefits in memory tasks, while both interventions produced comparable improvements in global cognition, executive function, and fine motor control. These results are detailed in Table 4.

DISCUSSIONS

This research compared 12-week AE and CARE interventions on physical fitness and cognitive performance in overweight and obese older adults. The findings revealed significant within-group improvements in both interventions, although differences in the direction and magnitude of these improvements was also evident.

Regarding body composition, the AE group exhibited significant decreases in weight, BMI, BFM, BFP, and WHR, indicating a stronger effect in weight and fat control. The CARE group also improved in fat-related measures but achieved a more notable gain in SMM, emphasising the value of resistance training for preserving and increasing muscle mass. Group comparisons supported these patterns: AE was more effective in lowering BFM and WHR, whereas CARE produced a greater rise in SMM, suggesting that the two training approaches complement one another in shaping body composition. Both groups had similar outcomes in weight and BMI, with small effect sizes, pointing to comparable benefits in overall weight control. These results align with earlier findings that resistance-inclusive training not only facilitates fat reduction but also more effectively maintains or augments muscle mass (Villareal et al., 2017; Rodrigues et al., 2023).

The differential effects between AE and CARE observed in the figures may be explained by their distinct physiological mechanisms. AE mainly enhances fat oxidation through elevated aerobic metabolism, thereby contributing to greater fat reduction (Muscella et al., 2020). In contrast, CARE combines aerobic benefits with resistance-induced muscle protein synthesis, increased muscle tension, and enhanced anaerobic capacity, which support muscle preservation and growth (McGlory et al., 2017; Fielding, 1995). These complementary adaptations explain why AE showed relatively larger improvements in fat-related indicators, while CARE demonstrated advantages in muscle-related outcomes. However, the between-group difference in BFP was not significant, likely because BFP reflects the combined influence of both fat and muscle changes, which may offset each other in this composite index.

Regarding physical fitness, both groups improved significantly across multiple tests, including 30s CS, 30s AC, SR, BS, 2.4m UG, SLS, and 2-min ST. Between-group comparisons revealed that CARE showed moderate advantages in upper limb strength (30s AC, ES = 0.235) and flexibility (SR, ES = 0.271), while improvements in other functional measures, including lower limb strength, mobility, balance, and endurance, were largely comparable between groups. This supports the role of resistance training in enhancing muscular function, which is practically important for reducing frailty and fall risk in overweight and obese older adults.

In terms of cognitive function, both AE and CARE groups showed significant within-group improvements across multiple domains, including global cognition (MMSE), working memory (DST-B), short-term memory (DST-F), visuomotor coordination (GPT), processing speed (SRT), and attention/executive functioning (TMT-A). Between-group comparisons revealed that CARE exhibited slight advantages in DST-F (ES = 0.168) and DST-B (ES = 0.073), suggesting marginal benefits for memory-related domains. The MMSE also improved more in the CARE group (2.46 points) than in the AE group (1.37 points), although the between-group effect size was small (ES = 0.104) and did not reach statistical significance. For other outcomes, including GPT, SRT, TMT-A, and TMT-B, both groups demonstrated similar gains, with small or negligible effect sizes.

Despite the lack of significant between-group differences, the numerical advantage of CARE in memory and global cognition may be related to mechanisms such as resistance training-induced upregulation of BDNF, enhanced prefrontal cortex activity, and increased cerebral blood perfusion (Ferris et al., 2007; Suo et al., 2016; Nakamura & Muraoka, 2018). Importantly, previous studies indicate that a change of 1–3 points in MMSE can be considered the minimal clinically important difference (MCID) for older adults. In this context, the 2.46-point improvement observed in the CARE group is likely to be clinically meaningful, while the 1.37-point increase in the AE group, although significant, may be closer to the lower threshold of clinical significance. Overall, both AE and CARE appear to enhance cognition, with CARE offering potential added benefits in memory-related functions.

From a public health perspective, these research findings highlight the multi-dimensional value of CARE in overweight and obese elderly people. Although AE has a significant effect on weight and fat control, CARE has more advantages in maintaining muscle mass, enhancing strength and improving cognitive status. Therefore, CARE can serve as a comprehensive intervention program for older adults, which not only delays the decline of physical functions but also maintains cognitive health, while enhancing their self-care ability and quality of life.

CONCLUSION

The findings indicate that a 12-week program of either AE or CARE led to notable improvements in body composition, physical fitness, and cognitive performance among overweight and obese older adults. While AE proved more effective for reducing weight and fat mass, the CARE protocol has more advantages in maintaining skeletal muscle mass and enhancing muscle strength. Both interventions were associated with cognitive gains, but only the MMSE revealed a significant group difference, with the CARE group achieving greater improvement.

Overall, CARE, in particular, may provide multidimensional health advantages in overweight and obese older adults. However, as most cognitive measures did not differ significantly between groups and individual variability in cognitive responses remains evident, further long-term studies are warranted. Future research should explore the neurobiological mechanisms underlying cognitive changes, including the use of biomarkers such as BDNF, and account for individual factors such as age and baseline cognitive status.

Study limitations

This study has several limitations. Recruiting participants through convenience sampling may restrict generalizability. The 12-week duration of the intervention may have been insufficient to produce significant cognitive improvement effects. The absence of physiological biomarkers limited the ability to examine underlying mechanisms. Future research should expand the sample size, extend the intervention period, and combine biomarker detection or neuroimaging techniques to assess the effects of different training programs on older adults' physical and cognitive health.

AUTHOR CONTRIBUTIONS

Conceptualization: Changyuan Zhao. Methodology: Changyuan Zhao. Data collection: Changyuan Zhao. Data analysis: Changyuan Zhao, Roxana Dev Omar Dev. Writing - original draft preparation: Changyuan Zhao. Writing - review and editing: Changyuan Zhao, Roxana Dev Omar Dev. Visualization: Changyuan Zhao, Roxana Dev Omar Dev. Supervision: Roxana Dev Omar Dev.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author, the data is not publicly available due to their containing information that could compromise the privacy of research participants.

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The impact of a congested fixture schedule on neuromuscular performance in young soccer players

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ABSTRACT

This study aimed to analyse the effects of successive matches on vertical jump performance in youth soccer players and compare responses between starters and reserves. Seventeen players participated in a regional tournament with five consecutive matches (two 40-minute periods with a 10-minute interval between periods), separated by 24-hour intervals. Internal competitive load was monitored using session-RPE, while vertical jump performance was assessed pre- and post-match for matches 1 and 5. Results indicated a significant reduction in vertical jump height among starters after the fifth match (pre: 37.24 ± 4.58 cm vs. post: 33.72 ± 4.66 cm, $p < .05$), whereas reserves showed no significant changes. Starters also experienced higher internal load, monotony, and strain than reserves ($p < .05$). These findings highlight the disproportionate impact of congested schedules on starters, emphasizing the need for tailored load management strategies to mitigate neuromuscular fatigue and maintain player readiness during competitions with excessively congested schedules. This study underscores the importance of individualized recovery protocols and strategic rotation of players to optimize performance and prevent overtraining. Coaches and sports scientists are encouraged to incorporate neuromuscular and internal load monitoring to enhance player health and performance sustainability in competitive settings.

Keywords: Sport medicine, Successive matches, Vertical jump, Session-RPE, Football, Adolescent.

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INTRODUCTION

Currently, the physiological demands of the modern soccer player are highly complex and depend on factors such as the player's position, the team's style of play, and the level of the opponent (Dolci et al., 2020; Williams, Drust, & Ford, 2023). In youth populations, sports competitions are usually organized over a short period and with a relatively high number of matches (Arruda et al., 2015; Moreira et al., 2016), and this organization often fails to consider the specific needs of athletes in training (Capranica & Millard-Stafford, 2011). Today, soccer players, especially at the youth level, can play many matches during a season, resulting in fewer adequate recovery periods between matches (Carling et al., 2018; Moreira et al., 2016; Pinto et al., 2021). As a result, official matches, there is significant psychophysiological stress on young athletes (Campbell, Irving, Bailey, Dilworth, & Abel, 2018; Dolci et al., 2020; Mehrsafari, Serrano Rosa, Moghadam Zadeh, & Gazerani, 2020), and this demand inherent in competitive play can lead to an increase in biochemical stress markers (de Lima Pinto, Fortes, Lemos, & Mortatti, 2019; Moreira et al., 2016; Mortatti et al., 2020; Pinto et al., 2021) and a reduction in physical performance (Pinto et al., 2021; Pinto, Menezes, Fonteles, & Mortatti, 2022).

In official matches, athletes can cover approximately ten kilometres, performing acceleration and deceleration actions that significantly strain the neuromuscular system (Dolci et al., 2020). Robineau et al. (2012) demonstrated that an official match leads to a reduction in speed and vertical jump capacity, so periods of congested matches are a potential factor in reducing the neuromuscular aspects of soccer players (Freitas et al., 2021). Still, on neuromuscular aspects, Rojas-Valverde et al. (2018) observed that due to accumulated fatigue and poor muscle recovery resulting from periods of congested matches in young soccer players, there is a decrease in muscle quality markers (maximum muscle displacement and contraction speeds). In this way, monitoring the training load can detect variations in fatigue and help maximize the athlete's physical potential (Furtado Mesa, Stout, Redd, & Fukuda, 2023).

Parallel to the monitoring of neuromuscular aspects, the acquisition of information on the internal training load that young athletes experience during official matches must be carried out. For effective management of the demands of training and competition, a holistic approach is essential. This includes understanding the interaction between internal and external load, well-being, psychological aspects, and the impacts of these demands on athletes' performance and health (Gabbett et al., 2017). Recent findings highlight that monitoring training load using tools such as session rating of perceived exertion (sRPE) can be crucial for coaches to prevent negative adaptations in young soccer players (Nobari, Kharatzadeh, Khalili, Pérez-Gómez, & Ardigò, 2021). In addition, sRPE shows a strong relationship with external load markers, making it a useful, simple, and inexpensive tool for monitoring internal training load (Marynowicz, Kikut, Lango, Horna, & Andrzejewski, 2020). In addition, considering the implementation of strategies to reduce discrepancies in training load between starters and reserves, such as individualized monitoring of training loads and matches, can help implement more balanced load management programs.

Given the change in neuromuscular performance during official matches in young starting players (Pinto et al., 2021, 2022; Rojas-Valverde et al., 2018) and its association with the accumulation of competitive internal load, it is pertinent to understand whether this behaviour is similar between the players who make up the team (starters vs. reserves). In contemporary soccer, clubs often compete in several matches throughout the season with inadequate recovery time. Insufficient rest and recovery between matches can expose players to the risk of competing before they have fully recovered (Julian, Page, & Harper, 2021). It is important to understand the dose-response relationship between consecutive matches and recovery over periods of training and competition. Therefore, this study aimed to monitor young players during a competition with

successive matches and to evaluate the effect of successive matches on training load and neuromuscular performance, comparing starters and reserves. It is hypothesized that successive matches will reduce the neuromuscular capacity of young soccer players, along with the accumulation of internal competitive load (sRPE, monotony, and strain). It is also expected that starting players will have greater negative impacts compared to reserve players due to less participation during matches and compensatory training of lesser magnitude than the official match.

MATERIALS AND METHODS

Participants

Seventeen young soccer players (16.6 ± 0.51 years; 175 ± 8 cm; 65 ± 7.9 kg) were selected for a regional competition with five successive matches. All athletes were associated with the club for at least a year, undergoing daily training five times a week in one shift (Monday: general force, special force, technical and tactical; Tuesday: coordination, speed, and agility, technical and tactical; Wednesday: flexibility and technical-tactical; Thursday: match training; Friday: general force, technical and tactical). Throughout the competition period, the athletes remained housed at the club, following the same schedule routine throughout the week. This study was performed in accordance with the Declaration of Helsinki and approved by the responsible person, approved by the Ethics and Research Committee of the Federal University Rio Grande do Norte (n°1.525.503).

Experimental design

The investigation was conducted during a regional tournament involving under-17 teams from the northeastern region of Brazil, in which they played five matches of the qualifying phase held in five consecutive days (with a 24-hour rest interval between each match). All matches occurred at the same location (soccer stadium) at 3:00 pm and lasted for 80 minutes (two 40-minute periods with a 10-minute interval between the periods) with a technical stop in each half for hydration. The participants went through the same process of conviviality in concentration during the week of the competition. Before (pre) and after (post) the first and fifth matches, the vertical jump height with countermovement was evaluated, and during the matches, the athletes' time in the field was monitored. Finally, approximately 30 minutes after the match session rating of perceived exertion was measured (Figure 1).

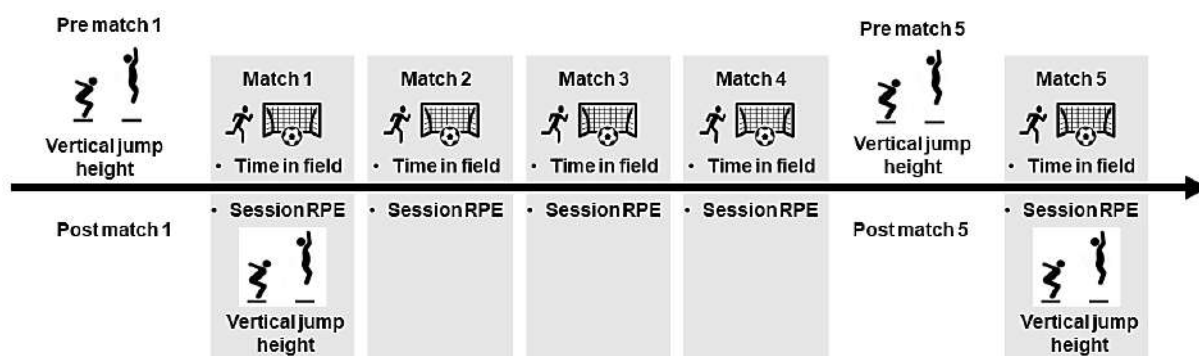


Figure 1. Study design.

Procedures

Competitive internal load

The competitive internal load was quantified at the end of each match using the sRPE method proposed by Foster et al. (2001). This method presents sufficient validity and applicability in different sports modalities,

including soccer (Haddad, Stylianides, Djaoui, Dellal, & Chamari, 2017). The values were obtained from the product of the perceived exertion value on the Borg CR-10 scale by the match duration (minutes). Thirty minutes after each match, players answered the question, “How was your workout?” avoiding any contact between players. The result, time x RPE product, is presented in arbitrary units and represents the internal load response to the physiological stress of the matches. The time in each athlete's field was computed by two evaluators to calculate the internal load as well as to quantify the sum of minutes of the players throughout the competition.

Vertical jump performance

Participants performed the vertical countermovement jump (CMJ) test on a contact mat (CEFISE®, Brazil) stored in the software *Jump System Pro*. Each athlete performed three maximal jumps with hands on the hips, separated by a rest of approximately 10 s. The jumps were performed on four occasions: pre- and post-match 1 and pre- and post-match 5. All players were largely familiarized with this procedure, which was usually performed during their training program.

Statistical analysis

Data are presented in descriptive statistics (mean, standard deviation, and 95% confidence interval). The Shapiro-Wilk test attested to the normality of the data. ANOVA of repeated measures compared the height vertical jump of the pre- and post-match in matches 1 and 5 in the general group and divided between starters and reserves; partial eta (η^2) was used for effect size in ANOVA, considering the criterion of Ferguson (2009): no effect ($ES < 0.04$), minimum effect ($0.04 < ES < 0.25$), moderate effect ($0.25 < ES < 0.64$), and strong effect ($ES > 0.64$). An independent t-test compared internal load, sRPE, time in field, strain, and monotony between starters and reserves. The effect size (ES) was measured according to Hedges', considering the sizes as small (0.20–0.49), medium (0.5–0.79), or large (≥ 0.8).

RESULTS

Table 1 shows the general values and those divided between reserves and starters for the athletes' external and internal competitive load during the competition. Starting players had higher sums of time on the field over the five matches ($p < .05$, MD: -204.3 ± 29.31 , 95% CI: -266.7 to -141.8) and higher average times on the field ($p < .05$, MD: -40.85 ± 5.86 , 95% CI: -53.35 to -28.36) compared to reserve players. In general, the intensity of the matches was “difficult” according to the sRPE, with starting players reporting higher intensity values compared to reserves ($p < .05$, MD: -2.82 ± 0.71 , 95% CI: -4.342 to -1.301). A greater sum ($p < .05$, 95% CI: -2359 to -925.7) and average ($p < .05$, 95% CI: -471.8 to -185.1) of competitive internal load was observed in starting players compared to reserves. Values for strain ($p < .05$, 95% CI: -1677 to -1721) and monotony ($p < .05$, 95% CI: -4.446 to -0.191) were also higher in starters compared to reserves.

Table 1. Internal and external load responses during successive matches.

	All (n = 17)	Starters (n = 10)	Reserves (n = 7)	t	p-value	ES
Sum time on the field (min)	245.49 (118.55)	329.60 (67.31)	125.33 (45.27)	6.96	<.001*	3.2
Mean time in the field (min)	49.09 (23.71)	65.92 (13.46)	25.06 (9.05)	6.96	<.001*	3.2
Session RPE (AU)	5.35 (2.00)	6.51 (1.48)	3.69 (1.39)	3.95	.001*	1.8
Sum internal load (AU)	1586.79 (1063.29)	2263.06 (814.49)	620.69 (410.62)	4.88	<.001*	2.2
Mean internal load (AU)	317.35 (212.66)	452.61 (162.89)	124.13 (82.12)	4.88	<.001*	2.2
Monotony (AU)	3.00 (2.29)	3.95 (2.53)	1.63 (0.79)	2.32	.034*	1.1
Strain (AU)	6594.36 (8375.85)	10402.46 (9215.56)	1154.21 (996.23)	2.61	.019*	1.2

Note. RPE: Rate of Perceived Exertion. AU: arbitrary unit. ES: effect size.

Figure 2 presents the vertical jump height before and after matches 1 and 5. There was a difference in vertical jump height between the pre- and post-match measurements ($F(3.16) = 8.468$, $p = .003$, $\eta^2 = 0.34$). Post-hoc analysis revealed a decrease in jump height in the fifth match (pre: 37.15 ± 3.71 cm vs post: 34.30 ± 4.58 cm, $\Delta = -2.84 \pm 3.39$; $p = .006$, 95% CI: 0.807 to 4.891).

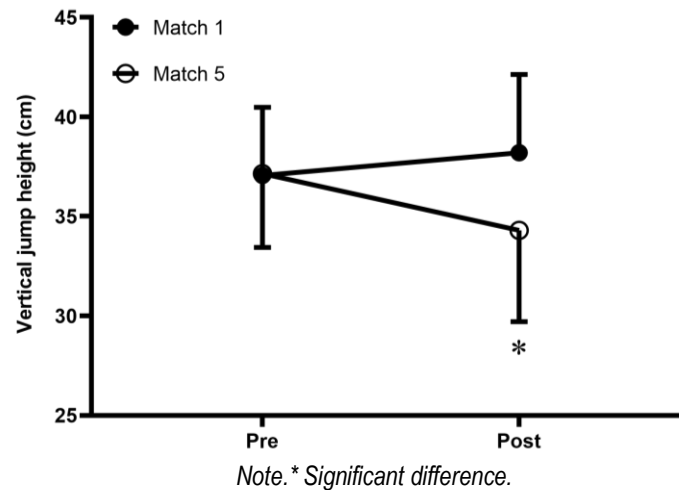


Figure 2. Vertical jump height in match-1 and match-5.

Figure 3 presents the vertical jump performance between starters (A) and reserves (B). Starting players showed a difference in vertical jump height between pre- and post-matches $F(3.9) = 10.590$, $p = .0040$, $\eta^2 = 0.54$. Post-hoc analysis revealed a difference only in the fifth match (pre: 37.24 ± 4.58 cm vs. post: 33.72 ± 4.66 cm; $\Delta = -3.52 \pm 3.10$, $p = .025$, 95% CI: 0.454 to 6.593). There was no significant difference in vertical jump height between pre- and post-matches among reserve players, $F(3.24) = 0.888$, $p = .4614$, $\eta^2 = 0.09$.

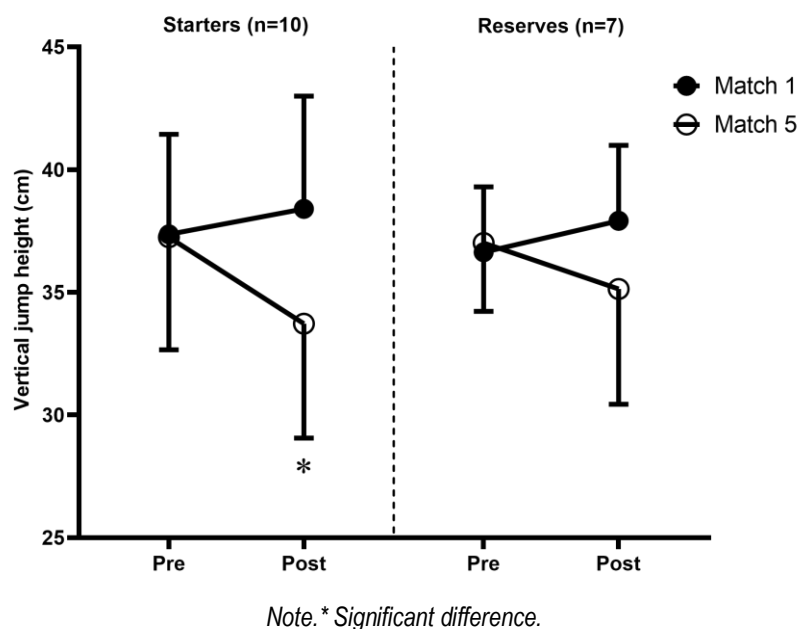


Figure 3. Vertical jump height between starters and reserves in match-1 and match-5.

Figure 4 presents the changes in vertical jump height between matches 1 and 5, overall and separately for starters and reserves. Comparing the change in vertical jump height for the entire team (matches 1 and 5), there is a greater reduction in the change of jump height after the fifth match ($t(16) = 4.821$, $p = .0002$, 95% CI: -5.745 to -2.236). This reduction is maintained only in starters ($t(9) = 4.690$, $p = .001$, 95% CI: -6.765 to -2.363) and is not observed in reserves ($t(6) = 2.130$, $p = .077$, 95% CI: -6.816 to 0.472).

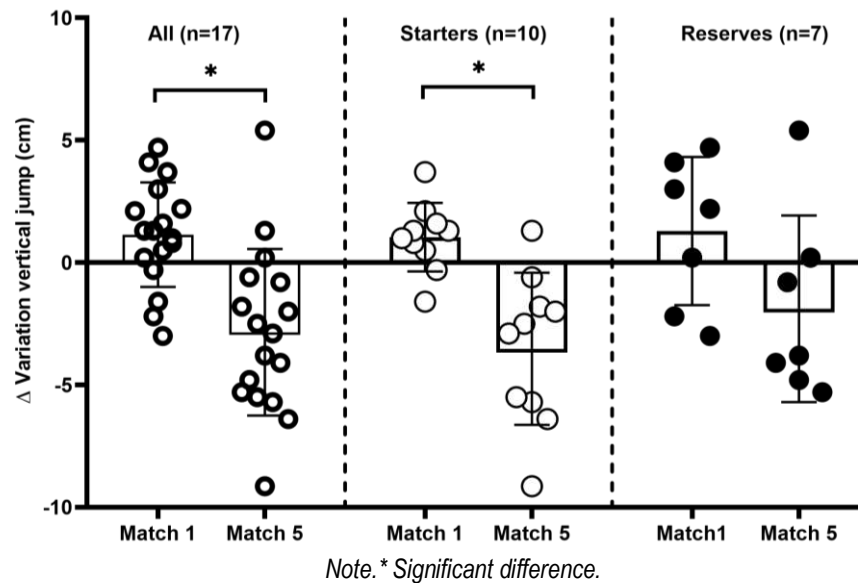


Figure 4. Variation in vertical jump height before and after match-1 and match-5 for all players, starters, and reserves.

DISCUSSION

This study aimed to analyse the effect of successive competitive matches on the neuromuscular performance of young footballers. The main finding was that young athletes subjected to successive matches showed a reduction in vertical jump performance. This reduction occurs in starting players who, in turn, have accumulated a greater internal competitive load, more time on the field, and greater monotony and strain compared to reserve players. The fact that young athletes reduce their vertical jump performance after matches has been reported in the literature (Curtis et al., 2021; Jagim et al., 2022), but few studies have observed this reduction in a scenario of successive matches. Pinto et al. (2021) observed reduction in vertical jump height in young athletes subjected to a sequence of four matches with 24 hours of recovery; this reduction is associated with accumulated fatigue from successive matches. In addition, these findings may also be due to the demands that official matches place on athletes, such as a high number of accelerations and a high distance covered (Curtis et al., 2021). Hader et al. (2019) state that external load variables present in official matches reflect acute and residual changes in neuromuscular responses and also noted that for every 100 meters of high-intensity running covered, the vertical jump can decrease by 0.5%.

Maintaining neuromuscular performance is crucial for specific actions during official matches, and relevant findings confirm that the reduction in neuromuscular performance is due in response to the demand (internal and external load) of matches (Marqués-Jiménez, Calleja-González, Arratibel-Imaz, & Terrados, 2022; Silva et al., 2018). Marqués-Jiménez et al. (2022) demonstrated that neuromuscular fatigue in soccer players is due to the activities performed on the field, such as acceleration and deceleration activities performed in the

match. In addition, the fact that official matches are played with short rest intervals (24 hours) can also be considered to reduce performance, given that a period of 72 hours after the match is not long enough to restore muscle damage, physical condition, and well-being to a state of rest (Silva et al., 2018). The results show that successive matches had an influence on neuromuscular performance only in the starting players, while the reserve players maintained their initial values after five successive matches. Due to the limited information on the drop in neuromuscular performance in starters and reserves in successive matches, these findings are difficult to explore; however, in young athletes, there is a clear reduction in neuromuscular performance as a result of matches with short time intervals (Pinto et al., 2021, 2022). Thus, although we can infer that a period of highly congested matches significantly compromises the physical fitness of soccer players (Saidi et al., 2022), these findings must consider the athlete's participation in the match.

Managing the training load in a sports team is a challenge for the coaching staff. Attesting to the initial hypothesis, starting players had greater internal and external load demands during successive matches. It has already been reported that players in the starting line-up are exposed to greater demands during training periods (Nobari, Alijanpour, Martins, & Oliveira, 2022). However, this study provides some of the first information on the demands placed on starting and reserve players during successive matches. Thus, players who completed an average of 65 minutes played reported “*moderate to high*” intensity values (RPE), while reserve players, who spent an average of 25 minutes on the pitch, reported “*moderate to light*” intensity values. Recently, Oliveira et al. (2023) confirmed our findings; the authors observed significantly lower values for reserve players in terms of cumulative time in training/match and internal load. Managing training loads during short competitive periods is a very difficult task, but it needs to be done, as the starting players must maintain their readiness for optimal performance during matches (Dalen & Lorås, 2019; Nobari et al., 2022).

From the disparities between starters and reserves in this study, it is possible to infer that starting players reduce their neuromuscular performance throughout the competition, which could necessitate the substitution of players to maintain the team's physical performance over successive matches and reduce the chances of injury (Nobari et al., 2021), as shown by the high monotony values. However, several factors determine team changes (Williams, Drust, & Ford, 2023), such as technical level and competitive maturity. In addition, the chances of winning seem to suffer from the effect of substitutions during youth competitions, and the chances of winning reduce even more when the match takes place in the knockout phase (Ribeiro, Siqueira, Pinto, & Silva, 2020). In addition to these aspects, it should be considered that reserve players in successive match situations may lose performance because they do not play during official matches, requiring stimulation at appropriate times.

This study offers a pertinent contribution to sports science, but some limitations can be listed for extrapolation to other populations. Firstly, there is a lack of data on external load (total distance covered, high-speed runs, number of sprints) and training load during matches between starters and reserves. In addition, future research should include tactical and performance variables to understand other interactions. Despite the limitations, the information presented offers information for young soccer athletes with significant ecological validity in a competitive environment.

CONCLUSION

In conclusion, during successive matches, young starting soccer players report moderate to high internal competitive load, accumulate high monotony and strain, and show reduced neuromuscular performance. The behaviour of these responses occurs only in starting players because they accumulate a greater internal competitive load, more time on the field, and greater monotony and strain during matches compared to

reserve players. As a practical application, it is recommended that coaches monitor internal and neuromuscular load responses during competitive periods with congested matches. This approach helps understand and minimize the impact of psychophysiological and neuromuscular stress, thus preserving the health of the players and maintaining the quality of the match. Additionally, it is recommended that match schedules be planned to ensure sufficient recovery time between matches, as well as controlling playing and training time for starters and reserves.

AUTHOR CONTRIBUTIONS

J.C.B.L.P., R.S.C.O., and A.L.M. conceived and designed the study, and they also collected the data. The authors, J.C.B.L.P., A.I.F., R.S.C.O., and A.L.M., analysed and interpreted the data, wrote the manuscript, and made significant changes. All authors have read and agreed to the published version of the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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Prevention of anterior cruciate ligament injuries in female soccer: Effectiveness and adherence to the FIFA 11+ protocol

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ABSTRACT

The main objective of this study was to evaluate the effectiveness of prevention protocols and rehabilitation strategies, particularly through the implementation of the FIFA 11+ program. Throughout the process, a detailed analysis of each athlete's physical condition was conducted, considering both previous injuries and potential muscular or joint weaknesses. This personalized approach allowed for the identification of specific prevention needs and the adoption of targeted interventions, aiming to reduce the risk of new injuries, especially in the most vulnerable joints, such as the knee and ankle. The study did not solely focus on the application of prevention protocols but also involved continuous comparison with historical data from previous seasons. This comparison enabled an objective assessment of the effectiveness of the adopted programs by measuring their impact not only in terms of injury reduction but also in the overall improvement of the athletes' physical performance and health.

Keywords: Sport medicine, FIFA11, Prevention, Anterior cruciate ligament.

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INTRODUCTION

The FIFA 11+ protocol is an injury prevention program developed by FIFA, primarily targeting football players of all ages and skill levels. It is designed to reduce the risk of injuries, particularly ligament injuries and muscle strains. Numerous scientific studies demonstrate that physical exercise represents one of the most effective forms of prevention for various diseases. In particular, football, being a team sport, proves to be an ideal activity for promoting socialization and improving physical fitness. Through the regular implementation of the FIFA 11+ program, it is possible to make football, both at the amateur and professional levels, a safer physical activity. It has been shown that the frequency of non-contact injuries can be significantly reduced through proper physical preparation. For this reason, FIFA and its Medical Assessment and Research Centre (F-MARC) have developed a specific injury prevention program called 11+. Clinical studies have demonstrated that the consistent adoption of the 11+ protocol can reduce the incidence of injuries by 30% to 50%. Based on these findings, FIFA has decided to promote this program globally within its federations. To this end, training programs have been developed for coaches, fitness trainers, referees, and technical staff to educate them on the principles and operational methods of the 11+ injury prevention program. Playing football requires a range of skills and abilities, including endurance, agility, speed, and both technical and tactical understanding of the game. These aspects are developed and enhanced during training sessions; however, football also carries a significant risk of injury. Therefore, an ideal training session should include specific exercises aimed at reducing the risk of injuries. The "11+" is an injury prevention program created by a group of international experts, based on practical experience accumulated through various prevention programs targeting amateur players aged 14 years and older.

It is a comprehensive package to be integrated at the beginning of training activities and should replace the conventional pre-training warm-up. A scientific study has shown that youth football teams that regularly use the "11+" as a warm-up practice have a significantly lower risk of injuries compared to those adopting a traditional warm-up routine.

Teams that adhered to the FIFA 11+ protocol at least twice per week experienced 37% fewer injuries during training and 29% fewer injuries during matches. Severe injuries decreased by nearly 50%.

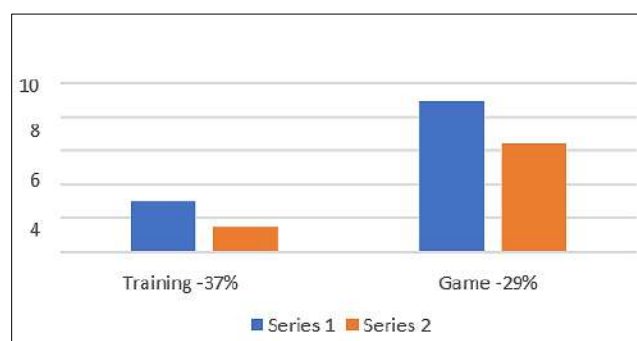


Figure 1. Injury in 1000 hours of activity.

MATERIAL AND METHODS

The FIFA 11+ protocol, originally developed to reduce injuries in men's football, has never been thoroughly studied in relation to the prevention of anterior cruciate ligament (ACL) injuries in women's football, despite these injuries being particularly common among female players. This was a key motivation for the research.

The primary aim of the study was to compare the results obtained by the women's team during the current season with those from the previous season, in order to analyse the effectiveness of implementing the FIFA 11+ protocol in injury prevention, with a specific focus on anterior cruciate ligament (ACL) injuries. The ACL is one of the most vulnerable structures in football, particularly for female athletes; thus, the objective was to determine whether the use of this protocol could significantly reduce the incidence of such injuries or, conversely, whether there were any complications or worsening outcomes compared to previous years. To conduct a thorough analysis, the study was structured in several phases, each aimed at exploring and understanding the group of athletes more comprehensively.

Phase one: Analysis of demographic characteristics and injury history

In this preliminary phase, key parameters of the players were examined, including year of birth, weight, height, body mass index (BMI), playing position, and previous injuries. These data not only provide a comprehensive overview of the physical profile but are also essential for better understanding potential predisposing factors for injuries, such as ACL tears. For example, greater height, higher BMI, or specific playing positions (such as goalkeepers or central defenders) may be risk factors for certain types of injuries.

The analysis of past injuries, including fractures, muscle strains, and previous ACL injuries, was crucial for identifying potential comorbidities or predisposing factors that could influence the effectiveness of the FIFA 11+ protocol. The examination of both quantitative and qualitative data will allow us to determine whether the implementation of the protocol has led to significant improvements in reducing injuries or whether there is still room for optimization and refinement. In this way, the study outlines a comprehensive framework that not only aids in the prevention of future injuries but also contributes to building a safer and more resilient physical profile for female football players.

Table 1. Athletes.

	Year	Weight (Kg)	Height (cm)	BMI	Role	Past injuries
Athlete 1	2008	59.5	163	22.4	Central	/
Athlete 2	2007	55.4	164	20.4	Defender	/
Athlete 3	2004	50.9	164	18.9	External	/
Athlete 4	2009	51.0	160	19.9	Defender	/
Athlete 5	2008	52.4	153	22.4	Fullback	Left ACL injury left meniscus microfracture
Athlete 6	2007	52.7	158	21.1	External	/
Athlete 7	2007	59.6	164	22.2	Defender	Tendon injury patellar
Athlete 8	2009	47.5	158	22.1	Central	Quarter Fracture right toe
Athlete 9	2009	62.0	159	24.4	Central	Bone oedema right malleolus
Athlete 10	2006	61.5	163	23.0	Defender	Hematoma from left knee contusion
Athlete 11	2009	76.5	160	29.9	Forward	Microfracture ankle malleolus left
Athlete 12	2008	72.7	157	29.5	Defender	Stretching M. Obliques
Athlete 13	2008	55.8	156	22.9	Central	Stretching m. adductors and fracture of the left ankle malleolus
Athlete 14	2006	62.3	161	23.9	Goalkeeper	Ligament injury Peroneal talus
Athlete 15	2008	54.5	157	22.1	Central	/
Athlete 16	2009	99.3	167	35.6	Goalkeeper	Injury leg. Peroneal talus and stretch m. Sartorio
Athlete 17	2008	55.7	164	20.7	Forward	Right ACL injury and fracture of the right malleolus
Athlete 18	2009	59.8	166	21.7	Goalkeeper	/

The age of the athletes ranges from 2004 to 2009, with a distribution of roles including defenders, central players, wingers, and goalkeepers.

The average BMI ranges from normal to overweight, with higher values observed among goalkeepers.

In terms of previous injuries, some players have experienced significant lesions such as anterior cruciate ligament (ACL) ruptures, fractures, and muscle injuries, while others have reported no injuries.

These preliminary data highlighted the need to focus not only on athletes who had sustained major injuries but also on those with minor muscular issues, in order to prevent the worsening of these conditions.

Special attention was given to players who had previously suffered ACL injuries, with the aim of preventing recurrence, which is often caused by muscular insufficiencies or premature return to sports activities without adequate strengthening.

To address this, specific muscle strengthening and functional rehabilitation protocols were implemented, focusing on improving knee stability, proprioception, and neuromuscular coordination, which are critical aspects for preventing further injuries.

At the same time, considerable attention was also given to other athletes presenting signs of muscular weakness, particularly in the thigh region.

This is because a lack of strength or imbalance between the flexor and extensor muscles of the thigh can predispose individuals to injuries such as strains, sprains, or even more severe lesions.

For these athletes, it was essential to constantly monitor potential muscular imbalances and motor difficulties, integrating specific exercises aimed at improving muscle strength, flexibility, and endurance.

Phase two: Analysis of the distribution of weekly training sessions, working closely with the athletic trainer and the coach

Training sessions were held three times a week, each lasting two hours, and included various exercises targeted at specific objectives depending on the focus of the day.

1) On Tuesdays, exercises aimed at increasing muscle strength:
Use of high hurdles with the objective of performing straddle jumps, followed by a rapid sprint. Use of low obstacles to perform straight-leg jumps with legs apart, followed by a final sprint aimed at increasing calf muscle strength. Direction change exercises using cones to improve agility.

2) Thursday: Exercises focused on endurance:
Fartlek training: This is a training method that combines running at varying intensities, alternating phases of high intensity with active recovery periods. This type of training is particularly effective for improving both aerobic and anaerobic endurance, as well as enhancing the ability to recover quickly between sprints and high-intensity actions typical of football (soccer).

3) Friday: Exercises targeting speed and coordination:
Shuttle runs: This training activity aims to improve speed, agility, and the ability to change direction rapidly. Shuttle runs involve running back and forth between two or more points spaced at regular intervals. This exercise trains both the aerobic and anaerobic systems while also developing muscular endurance and coordination. Ball possession drills: This methodology is used to improve players' technical, tactical, and cognitive abilities, particularly regarding ball control, game management, and decision-making under

pressure. This drill aims to develop the ability to maintain ball possession for extended periods, involving quick movements, precise passing, and continuous space-seeking.

Phase three: Introduction of the FIFA 11+ protocol as an integral part of the warm-up during training sessions

Its innovation lies in the structured combination of exercises that replace traditional warm-ups and are based on scientific evidence to reduce common football-related injuries, such as anterior cruciate ligament (ACL) injuries, muscle strains, and sprains.

The program lasts 20 minutes and must be performed at least twice a week during training sessions. On match days, it is recommended to perform only the running sections (parts 1 and 3 of the protocol), avoiding more intense exercises to prevent athlete fatigue. The quality of exercise execution is crucial: athletes must be continuously monitored to correct any errors and ensure proper technique.

RESULTS

The introduction of the FIFA 11+ protocol led to a significant reduction in overall injuries compared to the previous year, when the athletes did not follow a specific injury prevention program. This was particularly evident when compared to the "control group" (the athletes from the previous season). During this year, the "intervention group" recorded a significantly lower number of injuries, especially those related to muscle overload or fatigue, which are commonly seen in young female football players. The FIFA 11+ protocol proved effective in improving physical endurance and reducing risks associated with repetitive efforts. One of the most significant outcomes of the protocol was the complete absence of anterior cruciate ligament (ACL) injuries in the intervention group. In the control group from the previous year, two athletes had sustained ACL injuries, a severe injury that can seriously impact an athlete's sports career. This year, thanks to the adoption of the FIFA 11+ program, none of the players sustained ACL injuries, demonstrating that the protocol is a powerful preventive tool, especially for severe joint injuries that require long recovery times. Another key aspect was the improvement in the physical performance of the athletes, attributed to the consistent implementation of the FIFA 11+ program. The players showed enhanced endurance, agility, and muscle coordination, which are critical not only for injury prevention but also for optimizing on-field performance. The athletic preparation resulting from the application of the protocol allowed the athletes to engage in training and matches with reduced risk of overload and an overall improvement in motor skills. It is important to highlight the outcome for the two athletes who had sustained ACL injuries the previous year.

Thanks to the implementation of the FIFA 11+ protocol and a targeted rehabilitation program, both were able to fully recover and actively participate in the season without experiencing re-injury or further related damage. This not only demonstrated the program's effectiveness in preventing new injuries but also its role in promoting recovery and muscle strengthening.

Figure 2 clearly illustrates the benefits of adopting the FIFA 11+ protocol within the Pescara women's football team.

- General injuries: The intervention group showed a significant reduction compared to the control group.
- ACL injuries: No ACL injuries occurred this year in the intervention group, while the control group experienced 2 cases.
- Physical performance: Athletes in the intervention group demonstrated improvement compared to the control group.

- Recovery of athletes with ACL injuries: Two athletes from the intervention group, who had sustained ACL injuries the previous year, fully recovered and did not experience any recurrences.

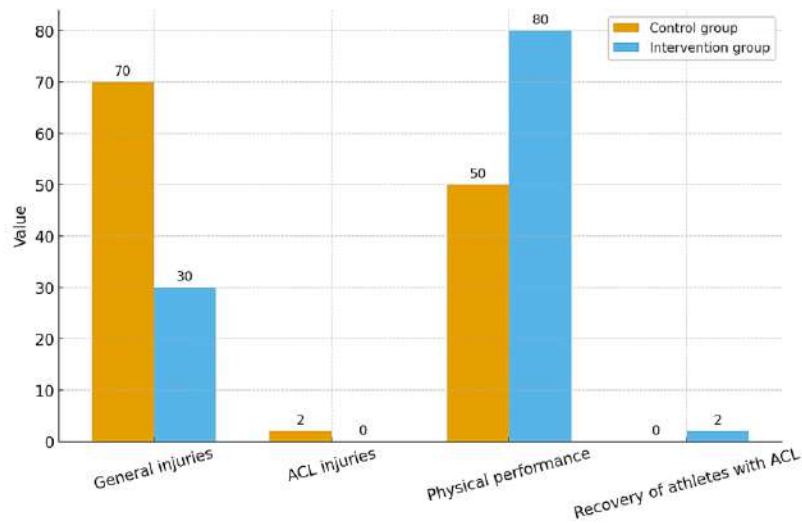


Figure 2. Comparison between the control group and the intervention group regarding the use of the FIFA 11+ protocol.

The study demonstrated a high effectiveness of the FIFA 11+ protocol for injury prevention, despite the sample being composed of female, non-professional football players with an average age lower than that of other studies.

DISCUSSION

The athletes involved, belonging to the Under-17 youth category, showed significant improvements both in injury reduction and physical recovery, demonstrating that the prevention program can be equally effective in a younger and less experienced population. To further investigate the impact of the FIFA 11+ protocol and determine whether there were similarities or differences with other studies in the literature, I decided to compare my results with a study titled "*Efficacy of the FIFA 11+ Injury Prevention Program in Male College Football Players*", conducted on male university teams (NCAA Division I and II). The main objective was to understand whether the effectiveness of the protocol was limited to specific groups or if it could be generalized to different populations, such as young female athletes compared to male collegiate athletes.

The comparison with this male population provided an additional perspective on the protocol's effectiveness in different contexts.

In the referenced study, the control group (without the use of the FIFA 11+ protocol) recorded a total of 665 injuries with an incidence rate of 15.04 injuries per 1000 athletic exposures and an average of 13.20 days lost due to injuries. In contrast, the group implementing the FIFA 11+ protocol showed a significant 46.1% reduction in general injuries, with 285 total injuries and an incidence rate reduced to 8.09 injuries per 1000 athletic exposures. The average time lost due to injuries also decreased by 28.6%, with an average of 10.08 recovery days. This allowed for a deeper understanding of the cross-sectional effectiveness of the FIFA 11+ protocol, demonstrating how it can be adapted and successfully used across various athletic populations, regardless of gender, age, or experience level. At the conclusion of this analysis, a table was developed to

provide a clear representation of the comparison between the female football team and a male team, both evaluated before and after the introduction of the FIFA 11+ protocol. The table allows for a detailed highlighting of the differences between the two groups across various key parameters: the total number of injuries, specific anterior cruciate ligament (ACL) injuries, changes in physical performance, and recovery time following injuries. Additionally, it shows how the incidence of these events changed in the absence of the protocol compared to when it was adopted. Therefore, the table serves as a summary tool to emphasize the advantages derived from the use of the FIFA 11+ protocol compared to its absence.

The differences in key parameters (number of injuries, ACL injuries, physical performance, and recovery time) are clearly outlined, providing a clear and visually immediate overview of the positive impact the protocol had on both study ed populations, female and male, despite differences in gender, age, and competition level. The comparison between the two groups highlights the differences in gender, age, and competition level, but also underscores how the FIFA 11+ protocol is versatile and adaptable to different types of athletes, regardless of these differences. In the youth female team, which is characterized by a higher vulnerability to ACL injuries, the benefits of the protocol were evident, with a significant reduction in severe injuries during the season. At the same time, in the male collegiate group, an improvement in general physical conditions was observed, with a reduction in both ACL injuries and other common football injuries, such as muscle strains and minor fractures. This type of comparative analysis further strengthens the idea that FIFA 11+ is a versatile and effective tool for injury prevention, adaptable to different athlete groups. Both in the female youth and male collegiate settings, the benefits were significant, suggesting that the systematic adoption of the protocol not only reduces injury incidence but also improves overall athletic conditions and shortens recovery times.

Table 2. Comparison between the two studies.

Pescara women's football team		Men's College Teams (NCAA Division I e II)	
Control group (previous year without FIFA 11+)	Intervention Group (this year with FIFA 11+)	Control Group (without FIFA 11+)	Intervention Team (with FIFA 11+)
General Injuries: More injuries than the intervention group.	General Injuries: Significant reduction in injuries compared to the control group.	General Injuries: 665 accidents with an incidence rate of 15.04 accidents per 1000 athletic exhibitions.	General Injuries: 285 accidents, a reduction of 46.1% compared to the control group.
ACL injuries: 2 cases of anterior cruciate ligament (ACL) injuries	ACL injuries: No cases of ACL injuries.	ACL injuries: Not specified, but included in the total number of injuries.	ACL injuries: Not specified.
Physical performance: Lower level than the intervention group	Physical performance: Improved physical performance. Two athletes with ACL injuries the previous year recovered without recurrence.	Physical performance: It has not been measured explicitly. Time lost due to injuries: 13.20 days on average lost due to injuries.	Physical performance: Not specifically measured, but injury reduction suggests better physical condition.
	Retrieval: Improvement, particularly for athletes with ACL injuries.		Recovery: 28.6% reduction (average of 10.08 days lost)

Before the introduction of the FIFA 11+ program, both groups exhibited a high incidence of general injuries, with significant cases of ACL injuries, which represent one of the major career risks for an athlete. The pre-FIFA 11+ comparison highlighted similar issues: high injury frequency, prolonged recovery times, and a

negative impact on athletic performance. In both teams, the absence of a structured prevention program left ample room for the occurrence of overload injuries, trauma, and, in particular, ACL injuries. With the introduction of the FIFA 11+ protocol, both the female Pescara Calcio team and the male university team showed significant improvement. The overall reduction in injuries, particularly ACL injuries, was noteworthy. In the female team, the absence of new ACL injuries throughout the season represents an exceptional result, while in the male university team, there was a 46.1% reduction in general injuries, with a substantial decrease in time lost due to recovery from injuries. This data demonstrates the effectiveness of the protocol not only in preventing injuries but also in facilitating faster recovery and a better return to athletic activities. In the case of the youth female team, the introduction of FIFA 11+ resulted in a notable reduction in injuries, especially concerning ACL injuries. In fact, no ACL injuries were reported in the intervention group, compared to two cases in the control group from the previous year. Physical performance of the athletes also improved significantly, particularly among those who had sustained ACL injuries in previous years, with full recovery and no recurrence. Similarly, in the male team, the adoption of the FIFA 11+ protocol led to a 46.1% reduction in general injuries, and although no specific data was provided on ACL injuries, the overall decrease in injuries suggests a positive impact on this population as well. Furthermore, the average time lost due to injuries decreased by 28.6%, indicating faster recovery times for the athletes.

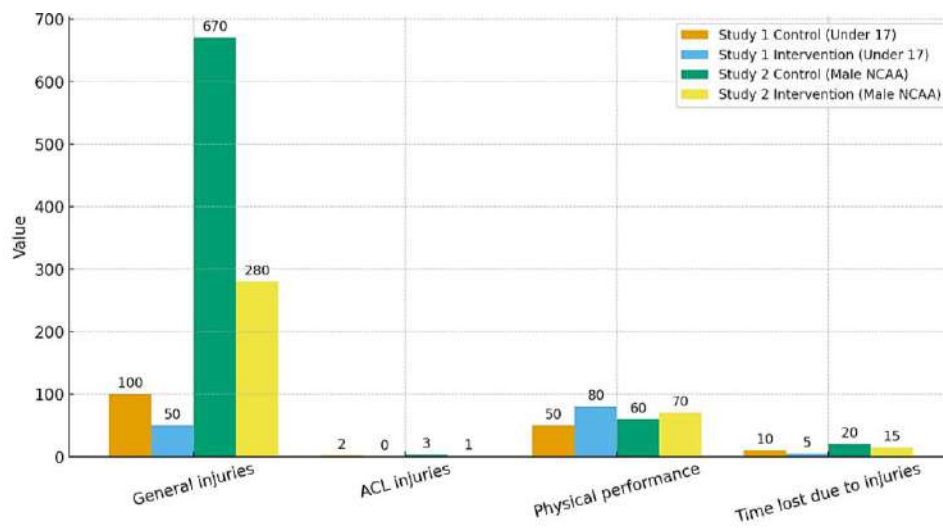


Figure 3. Comparison of studies: control vs. intervention.

The figure intuitively illustrates the differences in results obtained before and after the implementation of the FIFA 11+ protocol, allowing for a clearer understanding of the program's impact on key parameters such as injury frequency and physical performance.

This visualization enables a deeper understanding not only of the similarities and differences between the two studies but also provides a clearer view of the effectiveness of the FIFA 11+ protocol in injury prevention and improving the physical condition of athletes, regardless of gender or competition level. Both studies confirm the effectiveness of the FIFA 11+ program in reducing injuries, although they focus on different populations (female vs. male). In the youth female team, the absence of ACL injuries and the recovery of athletes who had sustained such injuries in the previous year represent particularly significant outcomes, while the male university study shows a global reduction in injuries. The comparison was useful in highlighting the differences in the protocol's effectiveness between athletes of different genders, confirming the program's efficacy in reducing injuries in both populations.

CONCLUSIONS

The implementation of the FIFA 11+ protocol as a preventive measure against anterior cruciate ligament (ACL) injuries in the Pescara Calcio Under 17 female team proved to be an extremely effective and beneficial intervention. The primary aim of this study was to evaluate whether the integration of this warm-up program, combined with specific exercises, could reduce the incidence of injuries, particularly ACL injuries, compared to previous seasons. Throughout the entire season, although some muscle strains were reported during certain matches, no ACL injuries occurred. This result is particularly significant, as ACL injuries are among the most feared for an athlete, not only because of the physical impact they cause but also due to the psychological consequences and the long recovery period they require. The complete absence of ACL injuries in a highly competitive context such as the Under 17 level suggests that the FIFA 11+ protocol played a key role in ensuring the necessary joint stability and protecting the athletes from potential severe injuries. Additionally, another important aspect revealed by the analysis was the general physical improvement observed even among athletes who had previously sustained ACL injuries. This data highlights not only the effectiveness of the protocol in preventing new injuries but also its contribution to fostering a solid recovery and reducing recurrences among players previously injured.

The progressive and specific exercises proposed by FIFA 11+ enabled the athletes to strengthen their physical capabilities, improving their endurance and preparing their bodies for intense efforts and the unpredictability of the game. The study thus underscores the crucial importance of injury prevention in sports, demonstrating that the adoption of structured protocols like FIFA 11+ is not only advisable but essential for ensuring the long-term health of athletes. Constant supervision and attention to the correct execution of exercises played a decisive role in the results obtained, significantly reducing the risk of injury and enhancing the overall performance of the team. To support these conclusions, the results obtained were compared with another scientific study in the literature that examined the application of the FIFA 11+ protocol in a sample of male athletes (NCAA Division I and II). This comparison further reinforced the effectiveness of FIFA 11+, demonstrating how the protocol, in both female youth soccer and male soccer, can significantly reduce the risk of injuries and the time lost for recovery. Although the studied populations differ in terms of gender, age, and competition level, the effectiveness of the protocol emerges as a common point between the two groups, highlighting the universal value of prevention through targeted exercises.

In conclusion, the adoption of the FIFA 11+ protocol in the female team resulted in tangible and positive outcomes. It not only succeeded in preventing ACL injuries but also contributed to the overall improvement of the athletes' physical condition, including those who had previously sustained injuries. This comparison with male athletes further confirms the validity of the program, emphasizing how its systematic application not only reduces the incidence of injuries but also improves athletic performance, thanks to enhanced functional strength, joint stability, and the physical response capacity to game stimuli. To achieve lasting results, it will be essential to continue implementing the FIFA 11+ protocol regularly, alongside careful and ongoing supervision to ensure proper execution and maximize the benefits of the program.

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. All authors read and approved the final manuscript.

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No potential conflict of interest was reported by the authors.

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Brazilian Amazonian Jatobá sap (*Hymenaea Courbaril* L.) as a hormonal modulator in soccer athletes

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ABSTRACT

To investigate the effects of Jatobá sap for eight weeks as an immunometabolic modulator in male soccer athletes. Phase 1: Phytochemical characterization (HPLC); Phase 2: (Jatobá) x (placebo). C-reactive protein (CRP), creatine phosphokinase (CPK), lactate dehydrogenase (LDH), alanine aminotransferase (ALT), aspartate aminotransferase (AST), and gamma-glutamyl transferase (GGT), urea, creatinine, cortisol, and testosterone were evaluated. The present study identified propelargonidin dimer and the flavonoids proanthocyanidin dimer, proanthocyanidin trimer, catechin, taxifolin, and caffeoylquinic acid glycoside. The placebo group showed a significant decrease in testosterone levels after the game about the pre-game time, a fact that did not occur in the supplemented group. Also, the supplemented group showed a significant increase in the levels of this variable in the 24-hour time about the post-game time, which was not observed in the placebo group. Regarding cortisol, both groups showed an increase in the post-game time with a return to basal levels in 24 hours. However, the stress of the match caused the placebo group to increase blood concentrations of this hormone by 150.5%, while the supplemented group increased blood concentrations by 59.3%. Supplementation modulated the testosterone/cortisol hormonal balance, with significant anabolic control between the groups after the match, and increase testosterone, reduced cortisol levels, and positively modulated the testosterone/cortisol ratio.

Keywords: Sport medicine, Amazonian plant, Immunometabolism, Sportomics, Health.

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INTRODUCTION

There are cyclical sports, such as running, cycling, and swimming, and acyclic sports, such as soccer. In this high-intensity acyclic sport, immunometabolism is required to the maximum, impacting the athlete's performance and health (Oliveira *et al.*, 2017). A promising approach in this context is using ergogenic resources, such as natural compounds with anti-fatigue and anti-inflammatory properties (Mucha *et al.*, 2021).

Previous studies have shown that oxidative stress generated by physical exertion can lead to complications such as fatigue, inflammation, and muscle injuries in athletes (Taherkhani *et al.*, 2021). In this scenario, plant-based antioxidant compounds have demonstrated the ability to offer protection against oxidative damage and inflammation (Maury *et al.*, 2020). Therefore, the intersection between different forms of sport and exercise methods and the action of natural compounds has aroused increasing interest in research into health and human performance (Nieman; Wentz, 2019).

In this context, the sap of the Jatobá tree, which belongs to the Fabaceae family, is a natural compound that has attracted attention for its antioxidant and anti-inflammatory properties, such as Propelargonidin dimer, proanthocyanidin dimer, proanthocyanidin trimer, catechin, taxifolin and caffeoylquinic acid glycoside (Boniface; Ferreira; Kaiser, 2017; Costa *et al.*, 2021A; Costa *et al.*, 2021B). In addition to other functions, these antioxidant compounds slow or inhibit the formation of reactive oxygen species (ROS) (Costa *et al.*, 2021A; Costa *et al.*, 2021B). ROS accumulates during intense exercise, and the antioxidant defence system may be unable to minimize its deleterious effects. As a result, a redox imbalance occurs that can cause impairment of the musculoskeletal system, thus leading to peripheral muscle fatigue (Fransson *et al.*, 2018).

The present study aimed to investigate the effects of eight weeks of ingestion of the sap of the Brazilian Amazon Jatobá tree as a modulator of biochemical and hormonal markers in male soccer players.

MATERIAL AND METHODS

Type of scientific research

This is a randomized, placebo-controlled clinical trial, with a quantitative approach, previously approved by the Research Ethics Committee (REC) of the União Educacional do Norte (UNINORTE), under opinion no. 5,159,860 and CAAE: 53503321.0.0000.8028 and following the standards present in resolution 674/2022.

Participants

Thirty male professional soccer players from a team in northern Brazil participated in the study. The selected participants were randomly divided into two groups of 15 people each, with one group using 50ml of Jatobá sap per day for 8 weeks (age 27.5 ± 3.65) and the other group using a placebo (maltodextrin) 50ml per day for 8 weeks (age 24.8 ± 3.43). Maltodextrin has been used as a placebo to study the effect of a wide variety of interventions, especially dietary supplements (Moreno-Pérez *et al.*, 2018).

This dosage of Jatobá is chosen following popular use by riverside dwellers and Indigenous peoples in the northern region of Brazil, more specifically in the State of Acre, in the city of Rio Branco.

In the first meeting, the groups received instructions on ingesting 50 ml of Jatobá (JB) and/or placebo (PLA), which was administered orally immediately before the start of each training session for eight weeks. Creatinine (CCR), Urea (URE), Alanine Aminotransferase (ALT), Aspartate Aminotransferase (AST), Gamma

Glutamyl Transferase (GGT), Creatine Phosphokinase (CPK), Lactate Dehydrogenase (LDH), Total Testosterone (TT), Cortisol and C-reactive Protein (CRP) were analysed, always before the start of the game, immediately after the game and 24 hours later.

Athletes who were physically fit to participate in training and games without symptoms or diagnosis of asthma, interstitial lung disease, cardiovascular, neuromuscular, or orthopaedic impairment were included. On the other hand, individuals who did not meet the inclusion criteria or were using other ergogenic resources, medications, or xanthines were excluded. After being informed of the risks and benefits of this research, all individuals signed the informed consent form (ICF).

Experimental design

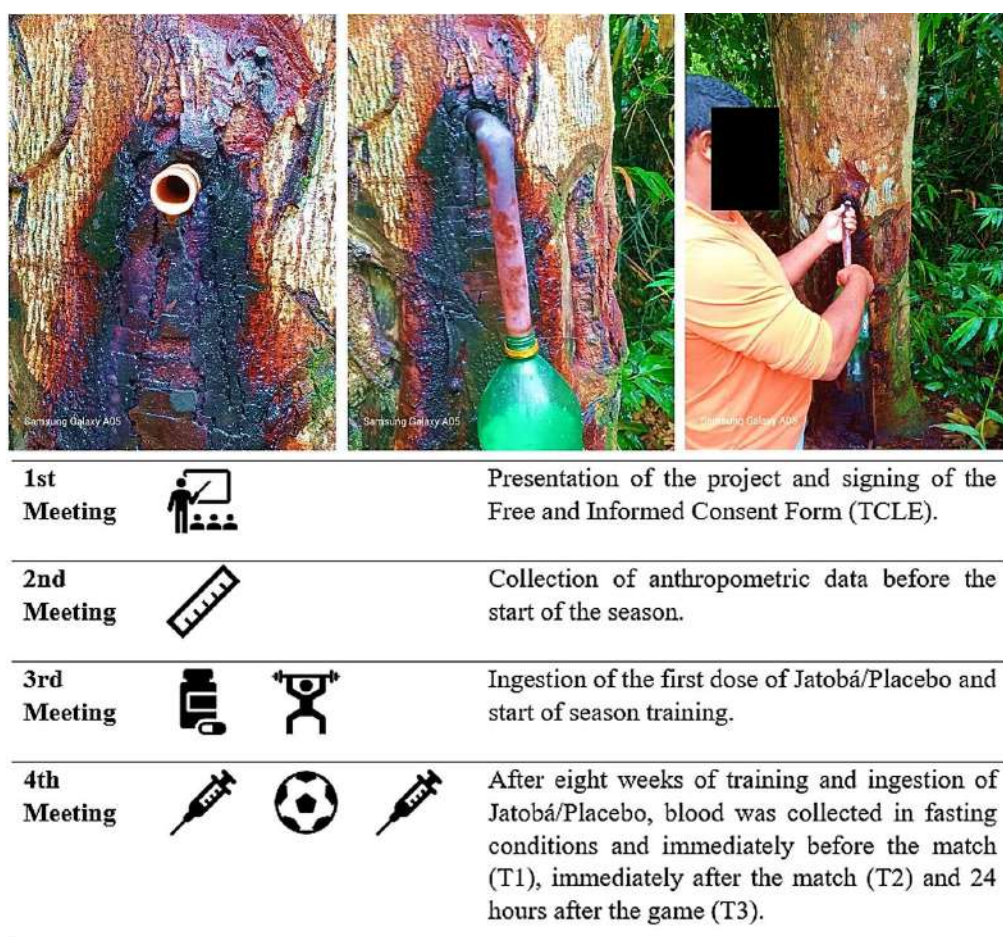


Figure 1. Experimental design.

Extraction of Jatobá sap

The extraction of the sap of the species *Hymenaea Courbaril* L. followed the protocols of the good practices guide for extracting Jatobá sap (IPAM/USAID, 2011). The Chico Mendes extractive reserve has already adopted these protocols after authorization from Ibama under no. 57286-1. The sap was collected for exsiccation under the following GPS coordinates – 9°59,50,67°59,2,2ws and identified at the Escola da Floresta with the help of the Botanist A.D.P. SOUZA and deposited in the herbarium of the Federal University of Acre (UFAC) with registration number UFACPZ 20025, Sisgen BF45A2.

Delimitation of the initial state

All subjects came to the laboratory before the start of the training season to collect anthropometric data. Data were obtained using an Inbody® 120 bioimpedance scale and a Sanny® ES2030 Standard stadiometer and will be presented in the results section.

Intake protocol

The intake consisted of 50ml per day for eight weeks of JB and/or PLA, considering the average weight of the sample in Table 2 in the results section, which is 78.5 kg for the control group and 79.7 for the Jatobá group.

The dosage used by riverside dwellers and indigenous people in the northern region of Brazil, more specifically in the state of Acre, in the city of Rio Branco, is between 50ml and 100ml per day. However, in a study published in 2022, the researcher used two doses of 50ml per day to evaluate the explosive strength of his volunteers (Cavalcante *et al.*, 2022), which justifies the choice of dose. The intake was supervised by a nutritionist participating in the project team and administered orally always immediately before the start of training. The athletes participating in the research declared that they were not using any other type of supplementation and that they followed a traditional regional eating routine as instructed by the team nutritionist, with the same diet for the entire team. For greater control of the data, the exact times of day were respected for collection and intake.

Side effects

A side effects questionnaire was applied every day before and after training during the research. The objective was to determine the volunteers' feelings regarding tolerance to the intake of JB or PLA, as well as to know if the volunteers followed the intake protocol and if they presented any adverse symptoms during the intake period, also classifying the frequency and severity of symptoms such as dizziness, headache, tachycardia, insomnia, gastrointestinal discomfort, and unusual or adverse effects, using the following parameters: no symptoms with 0, 1 (minimum: 1-2 times), 2 (regular: 3-4 times), 3 (medium: 5-6 times), 4 (severe: 7-8 times), or 5 (very severe: 9 or more times). Those who could not follow the protocol would be removed from the research. All individuals were monitored by the project nutritionist via phone calls and messaging app, thus ensuring that there were no adverse symptoms during the intake period.

Blood collection and analysis

A qualified nursing professional collected blood in a room prepared for the study. The individuals remained seated throughout the entire procedure. The blood was collected (± 5 ml) in the cubital fossa under vacuum in collection tubes with a clot activator (silica) sandblasted on the walls. Disposable vacuum collection needles were used.

After collection, the blood was deposited in a container suitable for transport and immediately taken to the Bionorte Biochemistry Laboratory. For the measurement of creatinine, the Labtest colorimetric kit (Reference 35; MS 10009010034) was used, for urea, the Labtest colorimetric-enzymatic kit (Reference 27; MS 10009010011) was used, for AST, the Labtest kinetic kit (Reference 109; MS 10009010018) was used, for ALT the Labtest kinetic kit (Reference 108; MS 10009010029) was used, for CPK the Labtest kinetic kit (Reference 117; MS 10009010019) was used, for GGT the Labtest kinetic kit (Reference 105; MS 10009010004) was used, for LDH the Labtest kinetic kit (Reference 86; MS 10009010056) was used, for PCR the Labtest kit Turbiquest Plus (Reference 331; MS 10009010198) by turbidimetry, for Testosterone the electrochemiluminescence method (ECLIA) was used, Labtest kit (Reference 4027; MS 10009010399), for Cortisol the electrochemiluminescence method (ECLIA) was used, Labtest kit (Reference 4063; MS

10009010399). All analyses were performed on the "Cobas Integra 400 Plus Analyzer and Cobas 411 Analyzer". The determinations of laboratory procedures were provided by the responsible biochemists of the laboratory itself, and all protocols were following the manufacturers' recommendations.

Data analysis

After organizing the data using "Data Wrangling," descriptive statistics of the variables were performed, with measures of position (mean, median, and mode), dispersion (deviation, standard error, and variance), and, finally, measures of shape (asymmetry and kurtosis). For comparisons between times and groups, since the variance in the biomarker values of this population is unknown, it is necessary to apply comparison tests for paired groups, adopting a significance level of 5%, $p < .05$ (error α). For this, the Shapiro-Wilk test was initially applied (due to $n = 30$ participants) to verify the normality between the data, which could result in two possibilities: A – If the value obtained was $p < .05$, the Mann-Whitney non-parametric test would be applied for two means and the Kruskal-Wallis non-parametric test for three or more. B – If the value obtained were $p \geq .05$, the Equal Variance Test would be applied, and if this test failed ($p < .050$), the Mann-Whitney non-parametric test would be applied for two means and the Kruskal-Wallis non-parametric test for three or more. However, if this test passed ($p \geq .050$), the paired T-Test would be applied for two means or the ANOVA for three or more.

Due to a predominance of non-normal distribution for the database (variables), non-parametric association methods were selected, which, since they are quantitative data, were the Spearman correlation, the elbow method for determining the ideal number of clusters, and the distance dendrogram by the Euclidean similarity index (agglomerative hierarchical cluster).

The graphs were presented with mean and standard deviation. SigmaPlot 14.5 (Academic Perpetual License—Single User—ESD Systat® USA), R and R Studio (Free version for Windows), and Past 4.03 (Free version for Windows) were used to carry out the different statistical tests and produce the graphs.

Calculations

Cohen d

$$d = \frac{X1 - X2}{\sqrt{(S_1^2 + S_2^2)/2}}$$

$d = 0.20$ (Small); $d = 0.50$ (Medium); $d = 0.80$ (Large)

Percentual variation

$$\Delta\% = \frac{(final - initial) \times 100}{initial}$$

Z score

$$Z = \frac{Individual\ score - Average}{Standard\ Deviation}$$

Euclidean similarity index

$$ED = \sqrt{\sum_j K=1 (ZXjp - ZXjq)^2}$$

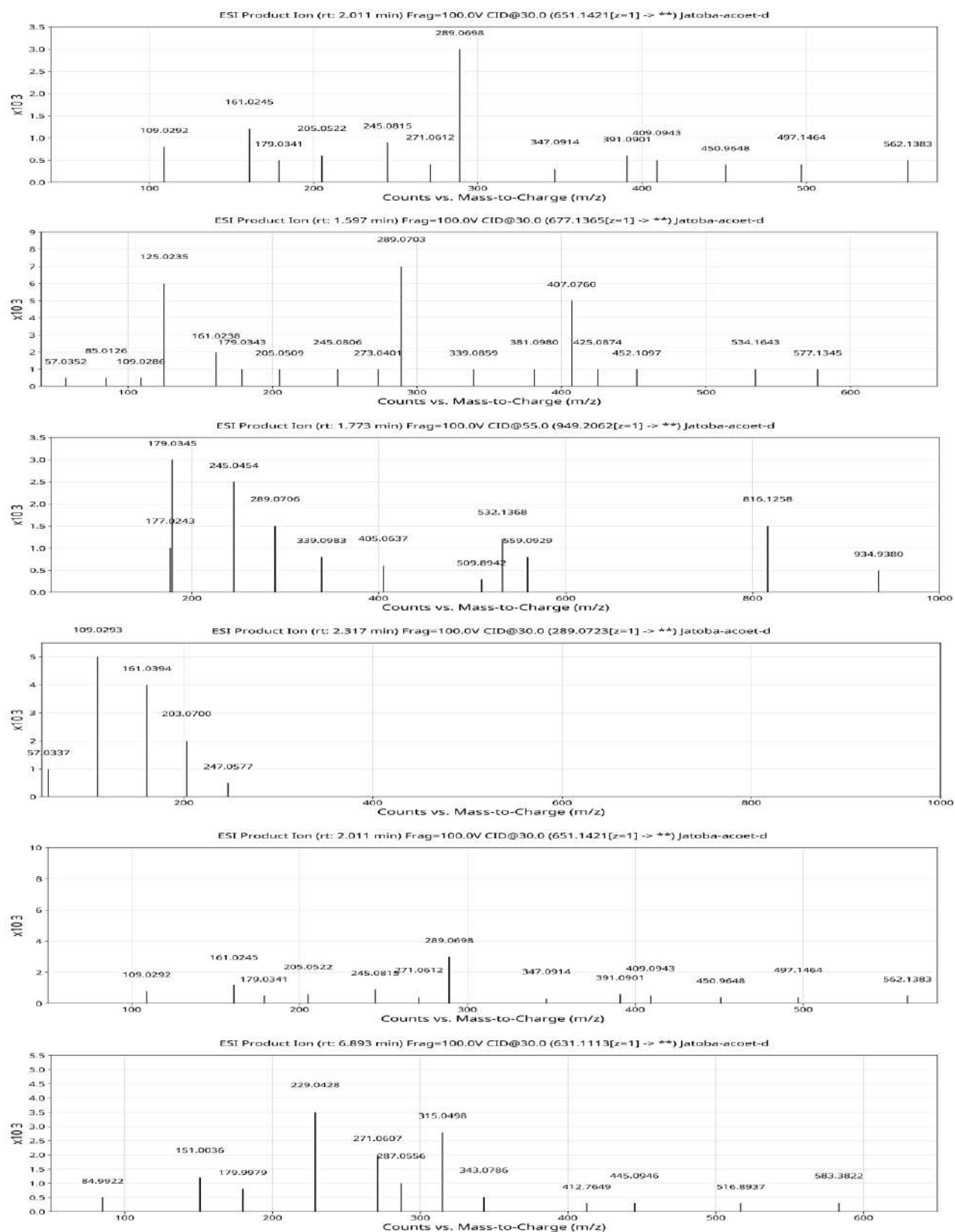


Figure 2. Phenolic compounds from Jatobá sap (*Hymenaea Courbaril* L.). (A) Properlagondin dimer; (B) Proanthocyanidin dimer; (C) Proanthocyanidin trimer; (D) Catechin; (E) Taxifolin; (F) Caffeoylquinic acid glycoside.

RESULTS

Phase 1. Phytochemical Characterization of *Hymenaea Courbaril* L.

The present study identified propelargonidin dimer (Figure 2A), a pigment that belongs to the anthocyanin category and is responsible for the orange-red coloration of plants. In addition, the flavonoids proanthocyanidin dimer (Figure 2B), proanthocyanidin trimer (Figure 2C), catechin (Figure 2D), taxifolin (Figure 2E), and caffeoylquinic acid glycoside (Figure 2F) were identified. High-performance liquid chromatography coupled with mass spectrometry was used to identify these compounds (HPLC-MS).

Phase 2. Study on the effects of using *Jatobá* sap for eight weeks on Soccer athletes

The anthropometric characteristics of the participants are presented in Table 1. Based on these data, it was possible to present descriptive statistics, and no differences were detected between the control group and the *Jatobá* group, all with $p > .05$. The data are presented as mean (position measurement), standard deviation and standard error (dispersion measurements), kurtosis and asymmetry (shape measurements).

Table 1. Subject characteristics (n = 30).

	Average		Standard Deviation		Standard Error		Kurtosis		Skewness	
	Placebo	Jatobá	Placebo	Jatobá	Placebo	Jatobá	Placebo	Jatobá	Placebo	Jatobá
Age (years)	24.8	27.5	3.43	3.65	1.03	0.98	0.47	-0.36	-0.79	0.20
Height (m)	1.81	1.77	0.09	0.06	0.03	0.02	2.07	-0.48	-1.24	-0.40
Body mass (Kg)	78.5	79.7	9.61	12.39	2.90	3.31	-0.84	2.39	-0.11	1.36
Muscle mass (Kg)	39.0	38.4	4.97	4.90	1.50	1.31	0.08	-0.82	-0.74	0.41
Fat mass (Kg)	10.1	13.4	2.56	6.83	0.77	1.82	0.31	3.14	0.62	1.49
BMI (Kg/m ²)	24.0	25.3	1.90	3.28	0.57	0.88	-1.63	0.86	-0.13	0.74
Fat (%)	13.1	16.4	2.70	5.90	0.81	1.58	-0.82	2.48	-0.33	1.73

Note. The values presented do not indicate statistically significant results. Categorical variables were analysed with the Fisher test. The Shapiro-Wilk test was applied to verify the normality of the data, with $p > .05$. The paired t-test was applied to verify the difference between two means (Parametric).

For the study's dependent variables, a holistic and integrated analysis was presented through the equations indicated in the "calculations" field of the methods and presented in Table 2, comparing the pre-game (T1), post-game (T2), and 24-hour post-game (T3) times. The analytes urea, creatinine, AST, ALT, and GGT did not show any significant difference or effect, indicating renal and hepatic safety for the participants.

CRP showed a difference between the times T1 x T3 and T2 x T3, with a greater percentage variation observed for the *Jatobá* group. For the control group, CPK showed a significant difference between the times T1 x T3, with the *Jatobá* group showing a difference between the times T1 x T2 and T1 x T3. The percentage variations once again were greater for the supplemented group.

Regarding LDH, the groups showed similar behaviours, with an increase between the times T1 x T2 and a decrease between T2 x T3, both of which were significant.

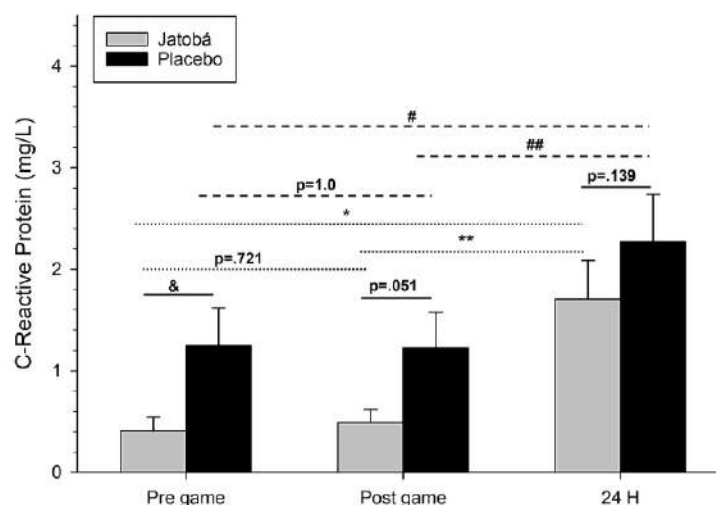
As for hormones, cortisol showed similar behaviour between the groups, increasing between T1 x T2 and decreasing between T2 x T3. However, it is noteworthy that the increase in cortisol in the control group was around 150%, while in the *Jatobá* group, it was only 58.3%, almost a third. In addition to the control group showing an increase of almost 300% in cortisol, the *Jatobá* group also showed a significant decrease in testosterone between the T1 and T2 times, which did not occur in the *Jatobá* group. Between the T1 x T3 times, while the control group still showed a reduction in testosterone levels (-2%), the *Jatobá* group already showed an increase (15.2%).

Table 2. Holistic and integrated view of dependent variables.

		Placebo			Jatobá		
		p - Value	Cohen d	Δ%	p - Value	Cohen d	Δ%
Urea	T1 x T2	.767	0.05	1.68	.906	0.04	-1.47
Creatinine	T1 x T2	.804	0.1	1.14	.857	0.07	-0.69
AST	T1 x T2	.921	0.02	-0.08	.835	0.03	-0.73
ALT	T1 x T2	.947	0.01	-0.73	.782	0.05	-2.72
GGT	T1 x T2	.974	0.001	-0.06	.909	0.01	-0.43
PCR	T1 x T2	1.0	0.02	-0.71	.721	0.16	183.2
	T1 x T3	.030	0.7	591.5	.001	1.2	1605.5
	T2 x T3	.030	0.8	590.3	.001	1,1	1274.4
CPK	T1 x T2	.067	0.8	50.7	.004	1.1	97.7
	T1 x T3	.016	1.1	96.2	<.001	1.6	149.9
	T2 x T3	.245	0.5	28.5	.373	0.3	24.7
LDH	T1 x T2	.001	2.3	38.4	<.001	2.8	53.7
	T1 x T3	.241	0.5	8.8	.073	0.7	16.0
	T2 x T3	.004	1.4	-20.2	<.001	1.7	-24.4
Cortisol	T1 x T2	<.001	3.7	150.5	.026	0.9	58.3
	T1 x T3	.288	0.5	-16.1	.325	0.4	-13.6
	T2 x T3	<.001	3.5	-65.0	.006	1.1	-42.1
Testosterone	T1 x T2	.023	1.0	-27.6	.251	0.3	-13.0
	T1 x T3	.922	0.03	-2.0	.434	0.3	15.2
	T2 x T3	.108	0.8	57.0	.027	0.5	40.2

Note. AST - Aspartate Aminotransferase; ALT - Alanine Aminotransferase; GGT - Gamma Glutamyl transferase; CRP - C-Reactive Protein; CPK - Creatine Phosphokinase; LDH - Lactate Dehydrogenase. The paired t-test was applied to variables with normal distribution and the Mann-Whitney test to those with non-normal distribution. Significant values are in bold.

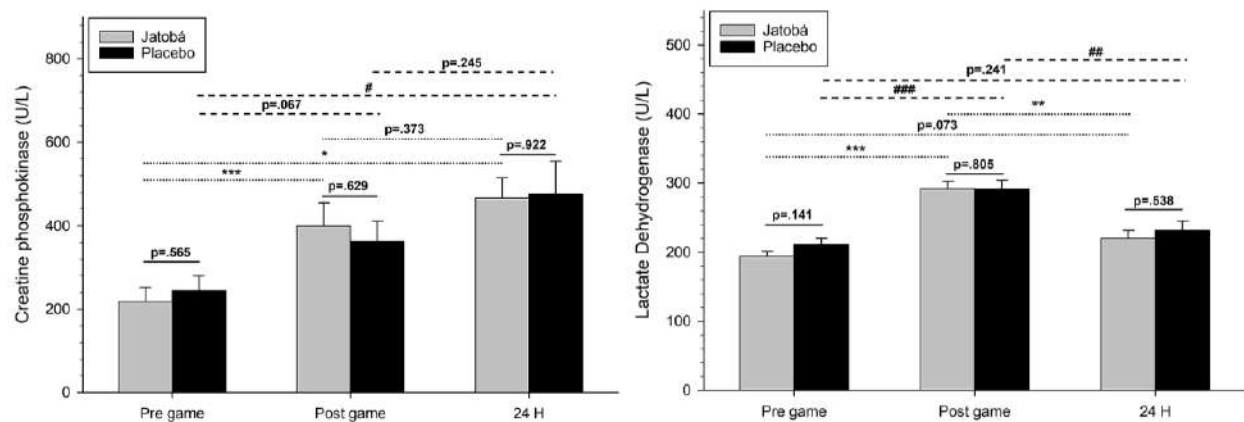
Regarding the observation of the absolute values of each biomarker, the PCR analysis (Figure 3) shows that professional soccer players, after 8 weeks of using Jatobá extract, presented a profile with less inflammation than the group that used the placebo (maltodextrin).



Note. Data are presented with mean and SEM. The paired t-test was applied for parametric variables and the Mann-Whitney test for nonparametric variables. Differences were considered significant when $p < .05$. * for the Jatobá group, # for the control group and & between groups.

Figure 3. Effect of treatment with Jatobá on the biochemical profile of CRP before, after and 24h after the game, reference value 0.3 to 1 (mg/dl).

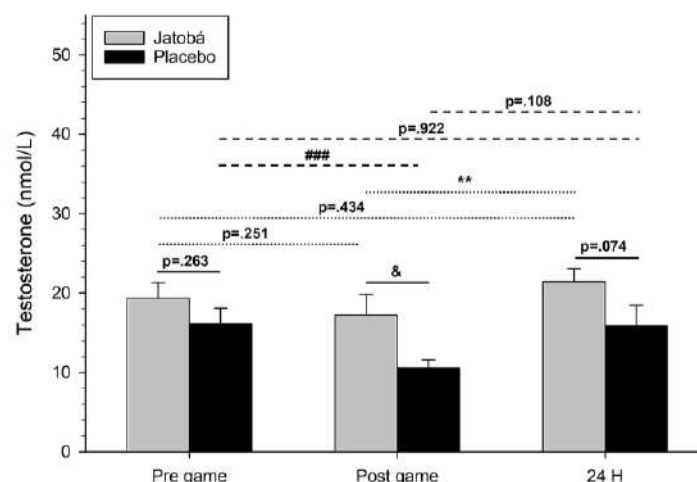
Still observing the absolute values, the muscle injury markers CPK and LDH had similar behaviour (Figure 4A and 4B), indicating that there was no differentiated impact on muscle tissue and that supplementation did not induce rhabdomyolysis.



Note. Data are presented with mean and SEM. Paired t-test was applied for parametric variables and Mann-Whitney test for nonparametric variables. Differences were considered significant when $p < .05$. * for Jatobá group, # for control group and & between groups.

Figure 4. Effect of treatment with Jatobá on the biochemical profile of muscle injury markers, namely (A) CPK and (B) LDH, pre-match, post-match and 24h post-match.

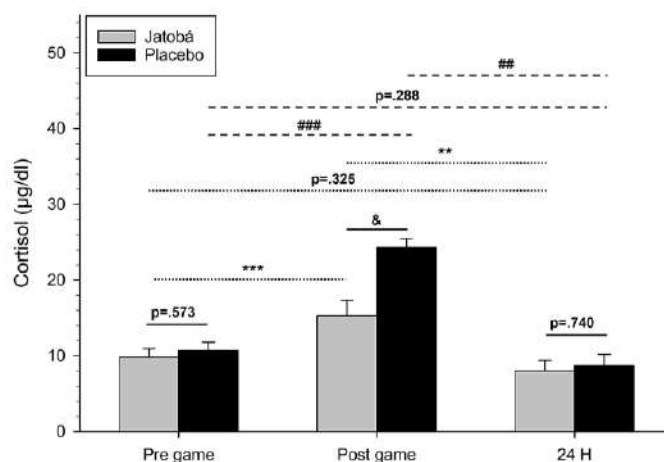
Moving on to the hormonal profile, the group of variables that drew the most attention started testosterone, which for the placebo group showed a significant decrease ($p = .023$) in the post-game period about the pre-game period, a fact that did not occur in the supplemented group. Also, the supplemented group showed a significant increase in the levels of this variable in the 24 hours of the post-game period ($p = .027$), which was not observed in the placebo group. A difference was also observed between the groups in the post-game period ($p = .021$), indicating that supplementation with Jatobá sap presented a positive modulation in the levels of this hormone (Figure 5).



Note. Data are presented with mean and SEM. Paired t-test was applied for parametric variables and Mann-Whitney test for nonparametric variables. Differences were considered significant when $p < .05$. * for Jatobá group, # for control group and & between groups.

Figure 5. Effect of treatment with Jatobá on the biochemical profile of testosterone before, after and 24 hours after the game, reference value 2.62 to 16.7 (ng/dl).

Regarding the other hormone observed, cortisol, it was possible to observe that both groups showed growth after the game with a return to baseline levels in 24 h, which was significant for both. However, the stress of the game caused the placebo group to increase the blood concentration of this hormone by 150.5% (effect of 3.5), while the growth of the supplemented group was 59.3% (effect of 0.9). The data revealed that supplementation modulated the testosterone x cortisol hormonal balance, with significant anabolic control ($p = .002$) between the groups after the game (Figure 6).



Note. Data are presented with mean and SEM. Paired t-test was applied for parametric variables and Mann-Whitney test for nonparametric variables. Differences were considered significant when $p < .05$. * for Jatobá group, # for control group and & between groups.

Figure 6. Effect of treatment with Jatobá on the biochemical profile of Cortisol before, after and 24h after the game.

What was stated in the previous paragraphs regarding testosterone (Figure 5) and cortisol (Figure 6) becomes even clearer when observing the testosterone x cortisol relationship since higher values indicate a more anabolic behaviour (more testosterone about cortisol), and lower values indicate greater catabolic stress (more cortisol about testosterone). In the pre-game period, the placebo group presented a difference from the Jatobá group in the order of -24%, a difference that was even greater between the groups in the post-game period (-61%) and remained 24 hours after the end of the match (-32%). These findings indicate better hormonal control modulated by Jatobá sap (Figure 7).

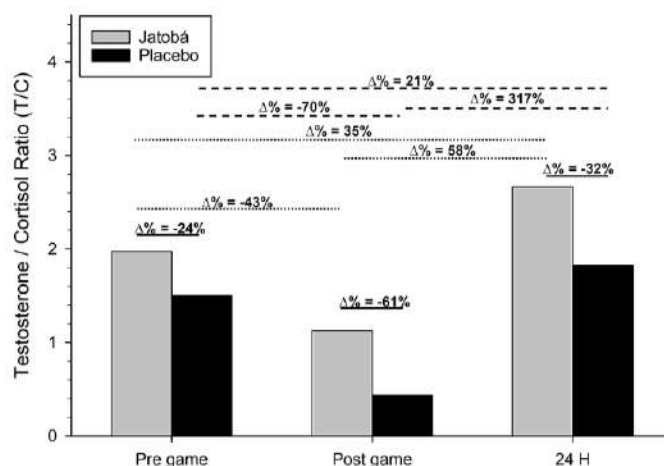


Figure 7. Effect of treatment with Jatobá on the Testosterone x Cortisol ratio before, after and 24 hours after the game. Δ% was used to demonstrate variation at all times of the study.

Since the study involves different variables, we investigated similarities and dissimilarities based on the groupings of all these study variables. Initially, we applied the Z Score to homogenize the measurement units of the variables. Then, we sought the most appropriate number of behaviour clusters using the elbow test (Figure 8A), indicating that three clusters were observed. Finally, we applied the Euclidean Similarity Index, with the distances presented by the agglomerative hierarchical dendrogram (Figure 8B). In this, a large cluster was clear, containing the variables CRP, type of supplementation, creatinine, testosterone/cortisol ratio, lactate, cortisol, testosterone, urea, GGT, AST, and ALT, leaving two other more dissimilar clusters, one for CPK and the other for LDH, which were more individualized in behaviour, showing no difference according to the supplementation (Figures 4 and 8B).

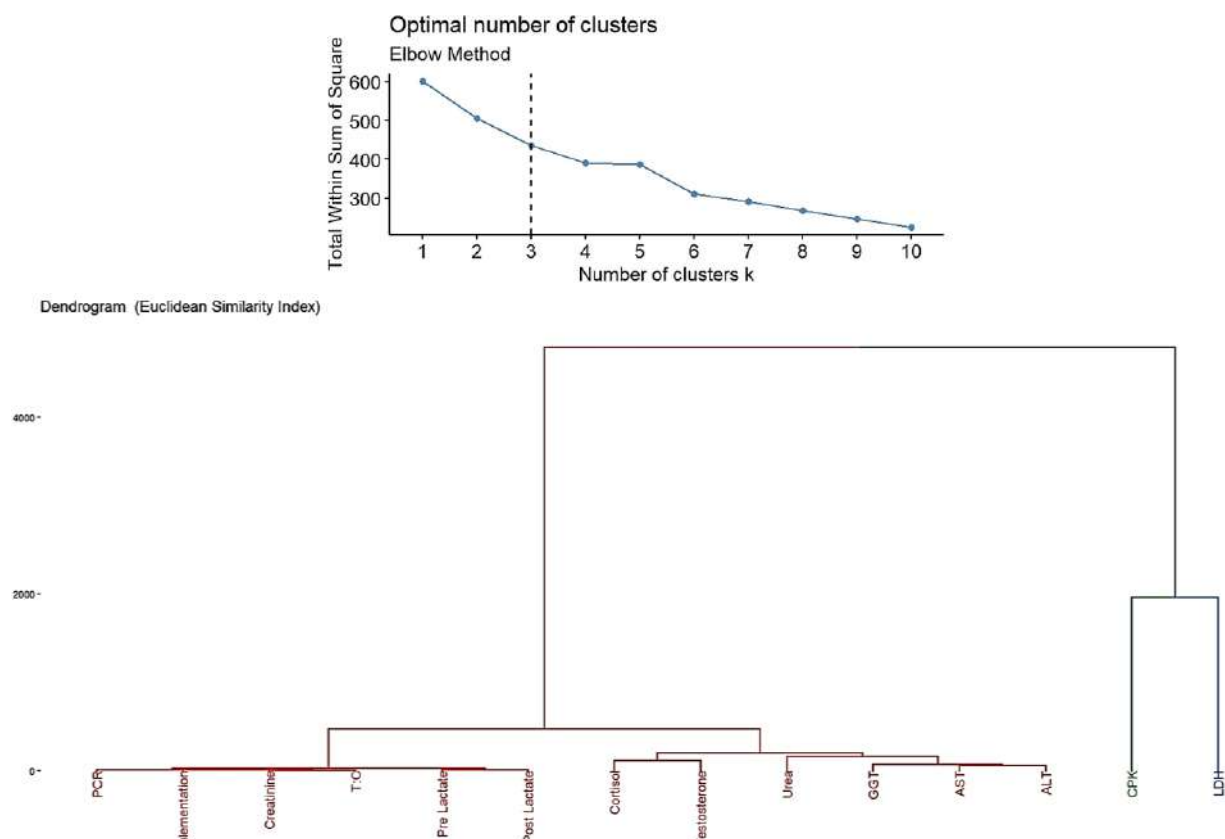


Figure 8. Elbow method to identify the optimal number of clusters (Figure 8A). Dendrogram using the agglomerative hierarchical method (Figure 8B).

DISCUSSION

Phytochemical research conducted with *Jatobá* (*Hymenaea Courbaril L.*) identified several phenolic compounds (Costa et al., 2021A). The present study identified propelargonidin dimer, a pigment that belongs to the anthocyanin category and is responsible for the orange-red coloration of the plants. In addition, several flavonoids were identified, including proanthocyanidin dimer, proanthocyanidin trimer, catechin, taxifolin, and caffeoylquinic acid glycoside. High-performance liquid chromatography coupled to mass spectrometry (HPLC-MS) was used to identify these compounds.

Our group had already demonstrated the antioxidant effect of Jatobá sap in mice (Costa et al., 2021A) and in vitro (Costa et al., 2021B). The present study is a pioneer in investigating the effects of Jatobá sap from the Brazilian Amazon on biochemical and hormonal indicators in male professional soccer players.

Previous studies analysed biochemical parameters in soccer players without the use of ergogenic resources, indicating an increase in CRP levels (Aldelkovic *et al.*, 2015; SILVA, J. R. *et al.*, 2014), CPK (Aldelkovic *et al.*, 2015; Pimenta *et al.*, 2016; Silva, J. R. *et al.*, 2014), and LDH (Coppale *et al.*, 2019; Aldelkovic *et al.*, 2015). In contrast, Requena et al. (2017) found that CRP and CPK levels remained stable after a break between seasons in a professional soccer team, with a significant reduction in LDH, which can be attributed to considerable drops in training volume and intensity (Raquena *et al.*, 2017).

In the present study, CRP showed differences between times T1 x T3 and T2 x T3, with a greater percentage variation observed for the Jatobá group. For the control group, CPK showed a significant difference between times T1 x T3, with the Jatobá group showing differences between times T1 x T2 and T1 x T3, with the percentage variations once again being greater for the supplemented group. Regarding LDH, the groups showed similar behaviours, with an increase between times T1 x T2 and a decrease between T2 x T3, both being significant.

In top-level soccer, one to three matches may be played over a week (Julian; Page; Harper, 2021). A wide range of physiological indicators have been employed to monitor the condition of athletes over prolonged periods (Heisterberg *et al.*, 2013; Silva, J. R. *et al.*, 2014). Specifically, hormonal markers (such as cortisol and testosterone) have been recognized as indicators of training-induced stress, making them relevant in the biochemical analysis of athletes (Hackney, 2020). Furthermore, the testosterone to cortisol (T/C) ratio has been used to assess the balance between anabolic and catabolic states in players (Urhausen; Gabriel; Kindermann, 1995).

Moving on to the hormonal profile, the group of variables that drew the most attention started testosterone, which for the placebo group showed a significant decrease ($p = .023$) in the post-game period about the pre-game period, a fact that did not occur in the supplemented group. Also, the supplemented group showed a significant increase in the levels of this variable in the 24 hours of the post-game period ($p = .027$), which was not observed in the placebo group. A difference was also observed between the groups in the post-game period ($p = .021$), indicating that supplementation with Jatobá sap presented a positive modulation in the levels of this hormone.

Regarding the other hormone observed, cortisol, it was possible to observe that both groups showed growth after the game, returning to baseline levels within 24 h, which was significant for both. However, the stress of the game caused the placebo group to increase the blood concentration of this hormone by 150.5% (effect of 3.5), while the supplemented group increased by 59.3% (effect of 0.9). The data revealed that supplementation modulated the testosterone x cortisol hormonal balance, with significant anabolic control ($p = .002$) between the groups after the game.

What was stated in the previous paragraphs regarding testosterone and cortisol becomes even clearer when observing the testosterone x cortisol relationship since higher values indicate more anabolic behaviour (more testosterone about cortisol), and lower values indicate greater catabolic stress (more cortisol about testosterone). In the pre-game period, the placebo group showed a difference from the Jatobá group of -24%, a difference that was even greater between the groups in the post-game period (-61%) and remained

24 hours after the end of the match (-32%). These findings indicate better hormonal control modulated by Jatobá sap.

The increase in cortisol levels for the placebo group can be attributed to the greater stress resulting from a more intense physical load, as well as the psychological pressure on the players (Santos *et al.*, 2012), which was prevented by Jatobá. Another study that used a 12-week training period with professional soccer players showed similar results (Silva *et al.*, 2011). Furthermore, (Michaidilis, 2014) examined cortisol fluctuations throughout the soccer season, revealing a significant increase in cortisol at the end of the season.

This study identified an increase in the T/C ratio after eight weeks of training with professional soccer players in the group that received the Jatobá extract. In part, this increase in the T/C ratio can be attributed to the estrogenic/antiestrogenic activity of isoflavones; it may also be due to an alteration in the biosynthesis and subsequent secretion of luteinizing hormone (LH), which acts to stimulate testosterone production in males (Kinahan; Budgett; Mazzoni, 2017).

Recent studies that did not use ergogenic aids demonstrated a significant decrease in the T/C ratio in professional soccer players (Andrzejewski *et al.*, 2021; Michaidilis, 2014; Saidi *et al.*, 2020; Silva *et al.*, 2011). The authors of these studies explain this decrease as resulting from neuromuscular fatigue, which can occur due to increased training intensity. This fatigue may be associated with a decline in physical performance (Saidi *et al.*, 2020; Silva *et al.*, 2014). Similar results were observed in the study presented here in the placebo group when we analysed the biomarkers of the T/C ratio. However, since this was not the focus of the study, we cannot establish a link with the decline in physical performance.

In part, these findings can be explained by the antioxidant properties of this extract due to its high content of flavonoids previously linked to anti-inflammatory effects (Costa *et al.*, 2021A; Costa *et al.*, 2021B).

Creatinine and urea analysis was performed as they are indicators of renal function (Maltai *et al.*, 2019). Previous studies have examined the effects of a dietary supplement containing a combination of flavonoids extracted from grape seeds and pine bark over 14 days in half-marathon runners, resulting in the prevention of increases in biomarkers associated with kidney damage (Semen *et al.*, 2020). There was no difference between groups or times for these markers, indicating the renal safety of their use.

Alanine aminotransferase (ALT), aspartate aminotransferase (AST), and gamma-glutamyl transferase (GGT) are enzymes frequently synthesized in the liver and are commonly evaluated as part of liver function tests (Giannini; Testa; Savarino, 2005). Elevated levels of these enzymes may signal inflammation or injury to liver cells (Benedict; Zhang, 2017). A recent study on molecular mechanisms related to curcumin, a polyphenol found in turmeric, indicated that the ingestion of this substance has several biological effects due to its antioxidant and anti-inflammatory characteristics, including liver protection (Xu *et al.*, 2018). At present, there was no difference between groups or times for these markers, indicating the hepatic safety of their use.

CONCLUSION

The study presented here examined the effects of Jatobá extract (*Hymenaea Courbaril L.*) for 8 weeks in professional soccer players, exploring a variety of biochemical and hormonal markers. In the phytochemical characterization phase by (HPLC-MS), the present study identified propelargonidin dimer, and the flavonoids proanthocyanidin dimer, proanthocyanidin trimer, catechin, taxifolin and caffeoylquinic acid glycoside. The

main findings of the primary phase point to the hormonal profile, where supplementation increased testosterone levels, reduced cortisol levels, and positively modulated the testosterone/cortisol ratio.

AUTHOR CONTRIBUTIONS

ABS, MJBF, KMS, ESL, RSLC, and RPMS planned and designed the study; ABS, MJBF, KMS, ESL, RSLC, and RPMS collected the data; ABS, JBC, RPMS, and LCOG processed and analysed the data; All authors participated in writing, discussing, and approving the final version of the study.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

DATA AVAILABILITY

All data generated or analysed during this study are included in this published article. The corresponding author can provide any other information by email.

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Training and detraining ratios: Optimizing exercise adherence in older adults

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ABSTRACT

Multicomponent training (MCT) has been shown to be beneficial, but more in-depth dose-response analyses are needed, especially in the long-term, due to low adherence and high heterogeneity among older adults (OA). This study aimed to develop an index to quantify and compare changes following training and detraining, regardless of adherence or follow-up length. This longitudinal, quasi-experimental study included 47 OA who completed one year of a MCT, with 25 continuing for a second year. To assess the impact of the intervention, Daily Training and Daily Detraining Ratios (DTR & DDR), defined as pre-post changes divided by training or detraining days, were used to analyse trainability in strength, cardiorespiratory fitness, agility, and executive function. Both ratios were converted into z-scores and graphically plotted. Considering the number of days trained and detrained, both physical and cognitive function improved significantly. Strength and cardiorespiratory fitness worsen largely during the second detraining, whilst agility declined more steadily. Inhibition remained stable or even improved during detraining. Noteworthy, physical function was more sensitive to training and detraining than executive function, and mobility enhancements confirmed helping to maintain cognition. Standardization and homogenization address adherence issues and allow comparisons of exercise programs that differ in nature and duration.

Keywords: Performance analysis, Executive function, Strength training, Physical fitness, Detraining, Trainability.

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INTRODUCTION

Research efforts in healthy older adults (OA) seek to show which is the best type of physical exercise intervention, which ideally means to be cost-effective, with larger functional and quality of life benefits, and smaller needs of time and psychophysiological demands for this population. Research interests are also focused on finding out the best dose-response strategies, the adherence generated by each type of exercise program, the already accepted need to tailor it, or above all, the need to analyse any improvement in the short, medium, and long term. Indeed, retention after physical-exercise cessation is a concern that has led to an increasing number of publications related to detraining (Grgic 2022; Leitão et al. 2023; Leitão et al. 2022; Modaberi et al. 2021; Venturini et al. 2022; Yang et al. 2021).

In this scenario, we find large discrepancies among different physical exercise training programs (PETPs), since there are wide ranges of age in the participants (Hakkinen et al. 2000; Toraman 2005), gender differences (Gretebeck et al. 2017), or differences in the training load parameters -i.e., intensity, volume and, mainly, frequency and duration- (de Jesus Almeida et al. 2020; Harris et al. 2007). The effect size is the statistic tool mostly proposed to compare their effects. However, PETPs are different in nature and duration, and up to our knowledge, effect size does not consider the frequency of training or detraining, nor the adherence. Similarly, the percentage of change (the delta) is always illuminative, but again it can lead to misunderstanding because it also discards duration and individual frequency of training.

Unfortunately, adherence has not been considered a relevant variable since short-term interventions always get a high rate. Notwithstanding, long-term programs hinder this rate because elderly people have commitments (medical care, family care, etc.) and adherence is known to decline over time (Mack-Inocentio et al. 2022; Picorelli et al. 2014). In fact, Gray et al. (2018) found a 45% dropout rate in a resistance training program of 48 weeks. Lower adherence as people increase their age and physical exercise programs lengthen, has devastating effects due to increases in immobilism and rate of functional impairment with aging (Farrance et al. 2016). Therefore, individual differences in the days of effective training (and detraining length) should be considered in the analyses to standardize the outcomes and avoid misinterpretations.

Hence, it is worthwhile to explore how long PETP's benefits remain, and which is the time-course of their training and detraining effects. Currently, meta-analysis can examine which PETP is effective using different statistical approaches. However, a recent study has highlighted the importance of how engagement, persistence and adherence influence cognitive effects after exercise interventions. Among their results, they concluded that adherence was a variable rarely reported in training programs despite being very important (Li et al., 2024). For this reason, the evolution of differences regarding the real time of individuals' training and adaptations (adherence) is a concern, so developing new index such as the *Daily-Training Ratio* (DTR), or the *Daily-Detraining Ratio* (DDR), which are defined as changes between sample moments divided by training or detraining days respectively, might be helpful or even a need.

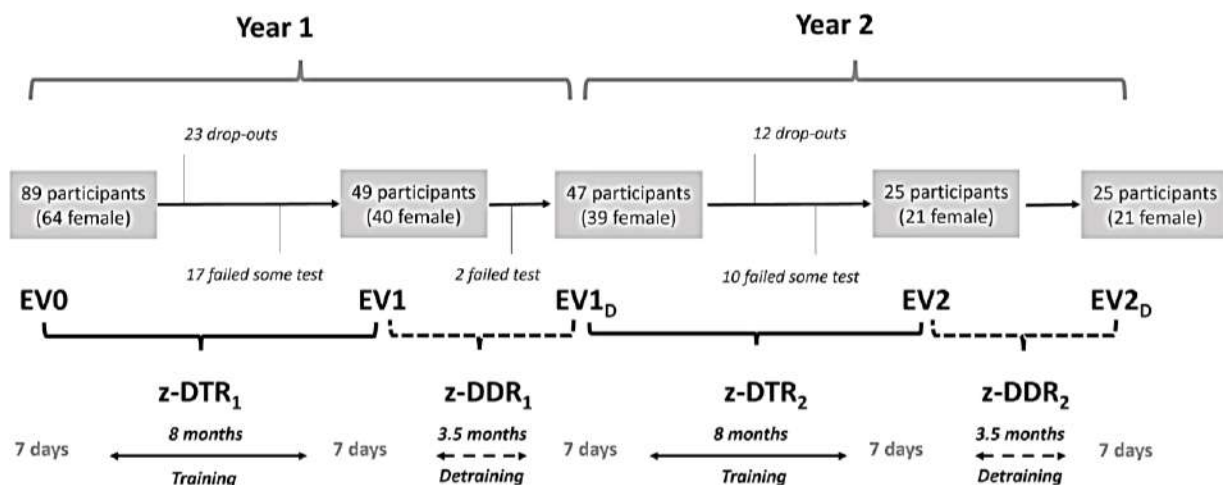
The aim of this study is to propose both ratios as a complementary tool to quantify trainability -changes through training or detraining- following two years of a multicomponent PETP tailored for OA. We hypothesize that quantifying changes in training and detraining regarding adherence (i.e. DTR and DDR), and its further standardization in z-scores (z-DTR and z-DDR), will give light to the real impact of the intervention on this population. Moreover, this method will allow to compare outcomes of different nature (e.g., neuromuscular, cardiovascular, and cognitive outcomes), as well as periods of training with different lengths, whatever the individual's adherence.

MATERIAL AND METHODS

Participants and experimental procedure

Since the starting of the EFAM-UV© (Blasco-Lafarga et al. 2016) project, many healthy OA have participated in this multicomponent training program developed in the sports facilities of the University of Valencia. Every year, physical and cognitive function assessments are conducted at the beginning and at the end of the program (October to May), resulting in 8 months for training and 3.5 for detraining, plus 15 days for testing (7 days in September and 7 days in June). Along the training periods, the program stops only one week for Christmas and one more for Easter to keep the rigour of the process and ensure physical exercise effects.

As already described Blasco-Lafarga et al. (2020), eighty-nine of these healthy OA were invited to participate in the present study and started training. Forty-seven subjects completed training and the whole evaluation on their first year in the program (39 women and 8 men, 71.02 ± 5.75 years; G1), that is, the pre-post training assessments (EV0 & EV1) and a third assessment after the corresponding detraining period which was the pre-training evaluation of the second year (EV1_D). Twenty-five of them (21 women and 4 men, 70.82 ± 5.18 years; G2) finished the second year in the program and completed its whole evaluation, again including the assessments after training (EV2) and detraining (EV2_D), which was the pre-training assessment on their third year in the program. Mean of adherence was 71% and 72% for the first and second year of the follow-up respectively. After a first traditional analysis considering the two years, but also training and detraining effects in each outcome separately (Blasco Lafarga et al. 2020), data have now been reanalysed by means of these two news standardization ratios. Two z-DTR and two z-DDR resulted from the 5 assessments as displayed in Figure 1.



Note. EVO: baseline; EV1 and EV2: assessment after the first (1) and second (2) training period; EV1_D and EV2_D: assessment after first (1) and second (2) detraining period. z-DTR: z-score from Daily Training Ratio; z-DDR: z-score from Daily Detraining Ratio. Upper lines and call texts describe the participants flow, from the initial 89 to the final 25 who completed the whole testing along the two years (from EVO to EV2_D). Continuous lines refer to the training period and dashed lines, to the detraining period.

Figure 1. Experimental procedure and flow chart.

All individuals were fully informed and signed their written consent to participate in the study approved by the ethic committee of University of Valencia (Certificate: H1363126067752).

Performance outcomes

According to Rikli and Jones (1999), physical function testing included the six-minute walking test (6MWT) to assess cardiovascular fitness; the 30s-chair stand test (CST) to test lower limbs strength; and the 8-feet timed up-and-go test (TUGT) to evaluate agility. Executive function (EF) was assessed through the Stroop test (Comalli Jr. et al. 1962), where the score obtained after 45 seconds was registered in each sheet. Only the sheet C was considered for further analysis, to assess the inhibition capacity (STROOP).

Body composition measures, executive function, agility and strength (in this order) were obtained during the first testing day, while blood pressure and cardiovascular fitness was assessed 48 h later in a second day to avoid interferences -see Blasco-Lafarga et al. (2020) for more details-.

Exercise training program

According to their investors (Blasco-Lafarga et al. 2016) EFAM-UV© methodology is based on a six-domain taxonomy, progressing in two levels. Starting from the retraining of the more basic motor skills (BS), which include improving gait pattern and postural control while moving forward, backward and laterally, tasks and constraints evolve to include manipulative skills like handling, transporting, passing, catching or throwing, as well as cognitive demands to improve executive function, memory, etc., which are consider complementary in the first level of motor literacy. Later on, the program integrates all the first level domains and introduces rhythm and complex functional motor skills to improve motor control as well as physical fitness in the participants. EFAM-UV© also evolves trough the physical exercise continuum from strength to bioenergetics, with cognition as a permanent target, supervised, tailored, and periodized (Figure 2). To see more details about this physical exercise intervention see Blasco-Lafarga et al. (2020).

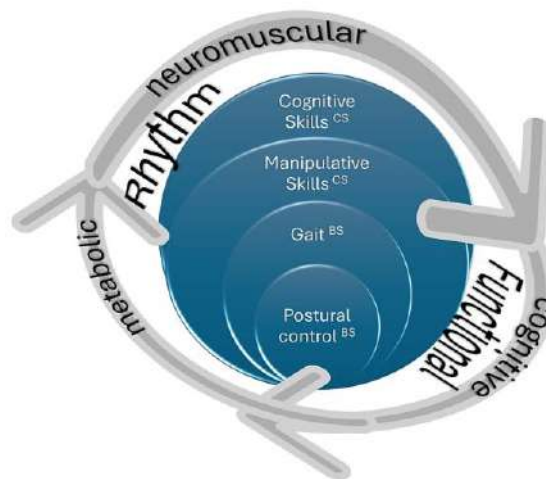


Figure 2. Taxonomy of the EFAM-UV© methodology (Blasco-Lafarga et al. (2020)), a multicomponent cognitive and neuromuscular orientation program specific for older adults

Ratios calculation

With the aim of homogenizing and later standardizing the individual performance, whatever the % of attendance to the training sessions and length of the program (and detraining period), the new ratios DTR and DDR were calculated (Figure 1). These ratios can be expressed as:

$$R = \frac{\Delta y}{t} \quad (1)$$

Where y refers to the name of the outcome; Δy is the change (positive for the gains and negative for the losses) in y between two periods, and t is the number of days of effective training for the DTR, and the total number of non-training days, for the DDR.

To compare among periods and outcomes the ratio was divided by the standard error of the corresponding mean i.e.:

$$\frac{\bar{R}}{s/\sqrt{n}} \quad (2)$$

with $\bar{R}$ being the sample mean of the studied Ratio (DTR or DDR), s being the sample standard deviation and n the given sample size. Notice that this is a z-score highlighting the differences with respect to a non-effect situation, making it comparable across times and outcomes.

$$z = \frac{\bar{x} - \mu}{SE} \quad (3)$$

Regarding notation DTR₁ (DTR₂) and DDR₁ (DDR₂) denoted the ratios for the first (second) year of training and detraining, respectively. A z- was added to the above notation to refer to the z-scores (i.e. z-DTR₁).

Statistical procedures

Statistical analyses were conducted with using R version 3.4.2 (2017-09-28). After testing for normality (Shapiro-Wilk test), and given the samples sizes, normality of all means was considered and, hence, t-tests were performed with a .05 significance level for determining unilateral regions of acceptance-rejection for the z-scores (see Figure 2 for results).

In particular, a null hypothesis of no effect (negative or 0 for the training periods and positive or 0 for the detraining periods) was tested against an alternative hypothesis indicating a significant positive (negative) effect in the DTR (DDR).

The acceptance-rejection regions were established according to the 0.05 quantile (with positive and negative signs) of a t-student distribution. Since the sample size differs for each outcome and period (from 22 to 47) the degrees of freedom of the t-Student distribution and the correspondent critical values also varied (from 1.68 to 1.72). With illustrative purposes a common acceptance-rejection region with 1.7 as the threshold value was established. This means that, for the training period a significant effect was considered if the corresponding z-score was larger than 1.7. Equivalently, for the detraining periods, a significant (negative) effect would be represented by a z-score lower than -1.7.

RESULTS

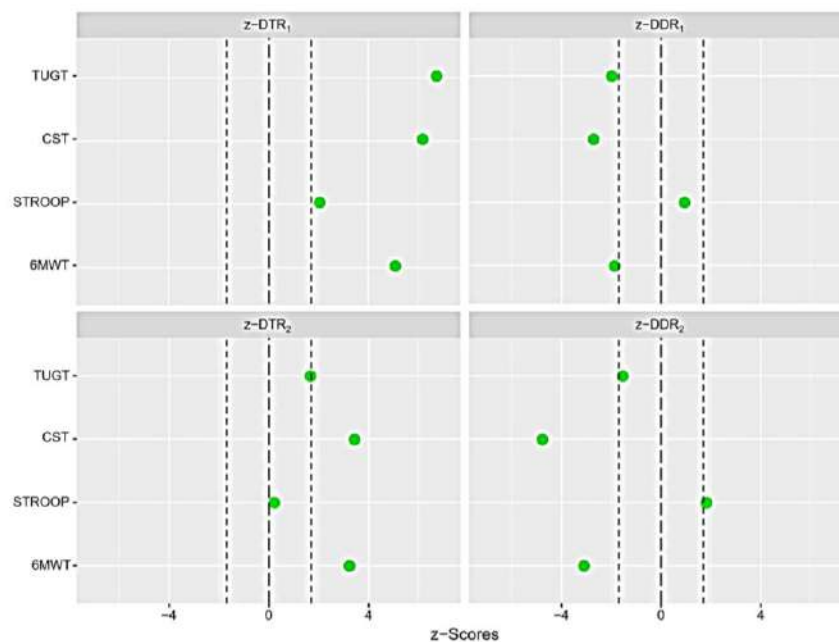
Table 1 shows raw data for physical and executive function variables for G1 (47 participants) and G2 (25 participants).

Figure 3 displays changes in physical (TUGT, CST & 6MWT) and executive function (STROOP), once standardized and converted into z-scores (z-DTR & z-DDR). Since these z-scores consider training and detraining impact -accounting for the time of effective training- on all the subjects who trained for one year in the EFAM-UV© program (z-DTR₁ & z-DDR₁), and on those who trained for two years (z-DTR₂ & z-DDR₂),

they allow to compare the trainability and retention of agility, strength, cardiovascular fitness, and inhibition capacity, along two training and two detraining periods.

Table 1. Sample characteristics and raw data for physical and cognitive function along two years of EFAM-UV©, expressed as mean (SD).

	1ST YEAR (N = 47)				2ND YEAR (N = 25)	
	EV0	EV1	EV1 _D	EV1 _{D'}	EV2	EV2 _D
Body Weight (kg)	68.14 (12.52)	67.54 (12.45)	67.91 (11.99)	66.48 (9.66)	65.28 (8.85)	66.1 (9.38)
Height (m)	1.57 (0.07)	1.57 (0.07)	1.55 (0.07)	1.54 (0.06)	1.54 (0.05)	1.53 (0.06)
SBP (mm Hg)	133.01 (23.47)	125.83 (15.99)	127.3 (15.99)	122.07 (15.18)	121.57 (13.33)	122.22 (16.7)
DBP (mm Hg)	74.16 (10.66)	68.48 (8.1)	72.04 (9.72)	70.3 (9.82)	70.72 (8.72)	73.57 (11.49)
TUGT (s)	6.85 (1.37)	5.69 (0.82)	5.8 (0.79)	5.7 (0.6)	5.42 (0.7)	5.57 (0.73)
CST (rep)	15.61 (3.08)	18.36 (3.82)	17.31 (3.96)	18.1 (3.68)	20.07 (4.63)	17.12 (3.55)
6MWT (m)	523.51 (64.96)	572.18 (61.92)	558.09 (71.71)	553.12 (71.87)	585.5 (75.13)	558.45 (80.2)
STROOP (u.a. score)	26.22 (8.54)	30.36 (11.08)	29.77 (10.89)	31.52 (10.04)	32.65 (8.3)	35.87 (11.14)



Note. Physical function: 6MWT (6-minute walking test), TUGT (8-feet timed up-and-go test), and CST (30s-chair stand test). Cognitive function: STROOP (Stroop test, inhibition). X axis presents z-scores: z-DTR1 & z-DTR2 (daily-training ratio in the first and second year; left side); z-DDR1 & z-DDR2: daily detraining ratio in the first and second year; right side). Neyman-Pearson significance test approach with a .05 significance level determines unilateral regions of acceptance-rejection when comparing a null hypothesis of no effect (negative or 0 for the training periods and positive or 0 for the detraining periods), against an alternative hypothesis indicating a significant positive (negative) effect in the DTR (DDR). Dashed lateral lines represent the critical values for rejecting the null hypothesis of non-effect, with the threshold value for common acceptance-rejection region at 1.7.

Figure 3. Changes in physical and cognitive function along two years of EFAM-UV©: z-Scores of daily-training and daily-detraining ratios (left and right, respectively).

A significant effect of the first training period was observed for each outcome with TUGT and STROOP showing the largest and lowest improvement, respectively. For the first detraining period, the only variable that did not show a negative z-score was STROOP (in fact it has still a positive value, although inside the rejection area). In the two remaining periods (during the second year) significant training and detraining effects for CST and 6MWT were observed. Meanwhile TUGT stayed in the limit of the rejection area during

both periods. Conversely, executive function was almost stationary after the second training period and remained positive (even in the limit of rejection) after the second detraining, showing the inverse effect.

A general overview explains the largest effect of training after the first year (Figure 3, left side: $z\text{-DTR}_1$ vs $z\text{-DTR}_2$), while neuromuscular and cardiovascular fitness (CST & 6MWT respectively) showed larger impairments in the second detraining (Figure 3, right side: $z\text{-DDR}_1$ vs $z\text{-DDR}_2$). Executive function improved continuously through the two years.

DISCUSSION

This study proposes a new method to quantify changes through training or detraining ratios following two years of physical exercise participation in the EFAM-UV© program. To the best of our knowledge, $z\text{-DTR}$ and $z\text{-DDR}$ are the first indicators capable of analysing and comparing performance changes following PETPs, regardless of their nature (strength, endurance, multicomponent, etc.), duration (i.e. the effective duration of training or detraining) or units of measurement (seconds, meters, etc.). Therefore, this approach addresses the issue of individual adherence differences and avoids the confounding influence of varying sample sizes or participant groups. In fact, both “*effect size*” or “*delta*” approaches to mean comparisons analysis, benefit from similar number of participants in all sample conditions to compare differences. Instead, this new measure allows for the use of different n values and different adherence levels (i.e., effective trained or detrained days) because both variables are integrated into the above-mentioned ratios. As hypothesized, $z\text{-DTR}$ and $z\text{-DDR}$ enable the analysis of short, medium and long-term training or detraining processes, facilitating adjustments to load and dosage in the short-term.

Compared to the analysis reported in the previous article (Blasco-Lafarga et al. 2020), the interpretation of the results has been modified by considering the specific days of training and detraining through to the ratios. The results of the first year of training changed minimally, and only the STROOP displayed significant differences when analysed with the ratios. Nevertheless, greater variations were observed in the subsequent periods analysed. After examining the first detraining, where no significant differences had been found with the traditional analysis (Repeated measures ANOVA), the ratios indicated a significant decline in all physical variables (CST, 6MWT and TUGT). During the second year of training, agility and cardiorespiratory fitness showed significant improvements according to the ratios, in contrast to the traditional analysis. Meanwhile, the CST and STROOP yielded the same results with both types of analysis. Finally, when the second detraining period was analysed using the ratios, the results also changed, revealing a significant worsening in cardiorespiratory fitness but a significant improvement in cognitive function. The changes in the results could be due to the fact that the ratios take into account the specific days of training (and non-training), whereas traditional statistics do not consider this factor and may therefore fail to accurately reflect what is truly happening. Or at least the weight of days of training/detraining underpinning and explaining the changes.

Once the $z\text{-DTR}$ calculation was performed, it became easier to compare the dynamics from the outcomes. Conditional capacities (lower limb strength and cardiovascular capacity) confirmed to be highly sensitive to training and detraining, reflecting both short- and long-term changes. This dynamic underscores the importance of training these two capacities after detraining periods, or at least implementing pre-established, even unsupervised strength exercises or routines to maintain the benefits of the physical exercise programs over longer periods -when supervision ceases, as noted by Geirsdottir et al. (2015). Another option is an eight-week retraining phase, as proposed Leitão et al. (2024), in which hypertensive women older adults improved their physical function after a three months of detraining. Since conditional capacities have been identified as two independent health indicators (Lee et al., 2010), their monitoring, maintenance, and

improvement should be prioritized due to their behaviour and their close relationship with the functional independence of older adults contributing to a better quality of life in parallel to their increased life expectancy.

On the other hand, the characteristics of the program (enriched exercises based on the dual-task paradigm and gait pattern involving changes of direction and rhythm) made agility highly susceptible to changes in all periods except for the second detraining phase. This may be due to a greater residual effect derived from training for two consecutive years through complex tasks, changes of direction and decision-making, as established by Donath et al. (2016) to improve this complex capability. Additionally, slower responses in cognition enhancement could explain why executive function was the only variable that exhibited a delayed response, despite training under the dual-task paradigm, as it improved after the second detraining period. These results are aligned with the theory of cognitive reserve, which states that the brain attempts to resist physiological or pathological changes associated with aging through neuroplasticity (Pettigrew et al., 2019). Notably, despite of López-Sáez de Asteasu et al. (2017) suggesting that adherence above 85% is necessary to enhance memory or executive function, EFAM-UV© was able to improve executive function in the long term, without neglecting other abilities that are equally important for the independent living of older adults. The fact that these two variables did not deteriorate during the second detraining period highlights the importance of long-term exercise programs, as their implementation helps preserve acquired benefits, leading to an improved quality of life by enhancing environmental awareness, decision-making, and action execution—thus facilitating daily life activities.

Similar to previous long-term studies (Mack-Inocentio et al. 2022; Oliveira et al. 2017), the sample decreased within periods over the years due to common aging-related issues (higher illness or familiar commitments). However, dropout rates remained within the range proposed by Geirsdottir et al. (2017). Despite being a supervised program, conducted in groups to promote socialization and carried out in a controlled environment -key aspects for maintaining adherence in women (Harris et al., 2020)- the decline in adherence over time could not be avoided.

z-DTR comparisons between physical and cognitive function in our study align with this need of larger adherence or more time of training to ensure cognitive improvements after physical exercise training. Unfortunately, we cannot conclude this based on previous studies, nor compared different trends in trainability, since, up to our knowledge, no previous study standardizes and homogenizes individual performance concerning actual individual participation.

Of uttermost importance, this new index is not particularly useful in the short term, as training days tend to be very similar for all users. But in long-term PETPs, adherence rates typically range between 70% or 85%, and the results obtained could be significantly affected. Thus, these ratios would allow for a more precise analysis of the number of training or detraining days and could even be used to compare differences between participants based on their attendance rates.

This study was not without limitations, primarily the significant reduction in the number of participants during the second year of training. However, recruiting older adults over an extended period (even years) is not an easy task. Further analyses and new research are needed to validate the z-scores, as they appear promising and could help refine in vivo training programs. Additionally, the ability to individually tailor these ratios would allow for the design of personalized programs so that all participants could benefit, despite varying levels of adherence. Moreover, monitoring adherence could help expand our understanding of the psychosocial benefits of long-term programs.

CONCLUSIONS

Summarizing, the ratios are more sensitive to small changes due to the tracking of training and detraining days. As a result, cardiorespiratory capacity, which did not show significant differences with traditional analysis, changed completely in its interpretation when using the ratios. Additionally, the two conditional abilities (CST and 6MWT) showed to be highly sensitive to both training and detraining, highlighting the need to reduce detraining periods or add maintenance exercises during any non-training period. Regarding agility and executive function, the ratios gave light that, thanks to long-term training, improvements showed to be maintained during the second detraining phase.

As a practical application, z-DTR and z-DDR could be proposed as a new method for comparing different programs and determining which is most effective in terms of objectives, pathologies, and adherence rates regarding participants' physical and cognitive conditions. These ratios could be a simple complementary tool for comparing physical exercise interventions by adding a necessary information, such as adherence. This way, policymakers and fitness trainers should recommend or even prioritize PETPs with higher z-DTR and lower z-DDR for specific populations -i.e., those that generate the most significant changes during training and the highest retention rates during detraining. Indeed, these findings and reanalysis helped to confirmed that the physical and cognitive benefits following EFAM-UV© methodology were highly valuable in developing community policies aimed at creating specific physical exercise programs for older adults.

AUTHOR CONTRIBUTIONS

All authors have contributed to the published work and agree to its publication in JHSE. Specifically, conception and design: AC, AF, CBL; training program and collected data: AC, AR, PM; analysis and interpretation of the data: AC, AF, CBL; drafting of the paper: AC, AF, CBL; writing—review and editing: AC, AF, AR, CBL, PM. All the authors approved the final version to be published and agree to be accountable for all aspects of the work.

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Curvilinear sprint in floorball: Association with linear and angle-dependent change of direction performance

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ABSTRACT

The study aimed to determine associations between curvilinear sprint (CS), angle-dependent change of direction (COD) and linear sprint (LS) performance times and deficits. Forty-eight male floorball players performed 20 m CS and LS, 45° COD (5 + 5 m) and 180° COD (5 + 5 m) tests. The deficit was calculated as the difference between the limb CS, 45° COD or 180° COD, and LS time. Significant differences were found between right and left limb performance in CS (5 m, 10 m and 15 m), 180° COD and deficits ($p < .05$), but no differences in 45° COD times and deficits ($p > .05$). The CS and 45° COD deficits were higher when the distance length increased, whereas the CS deficit stabilized at 20 m from both sides. Only the left limb 5 m CS deficit was associated with 45° COD deficits ($r = 0.31$ to 0.34 , $p < .05$). These findings suggest that a deficit is a useful practical tool for assessing the effectiveness of athletes LS capabilities across different trajectories, as well as for identifying potential biomechanical similarities among components. Practitioners can benefit from integrating different speed components in training to enhance CS performance in floorball.

Keywords: Performance analysis, Multi-directional speed, Floorball, Change of direction, Linear speed, Curvilinear.

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INTRODUCTION

Floorball is an indoor contact team sport in which athletes must perform frequent technical and high-intensity multi-directional movements, such as linear and non-linear accelerations and sprints, rapid change of directions from different angles, and decelerations (Tervo & Nordström, 2014). A well-developed combination of multi-directional movement components ensures the effective implementation of tactical and technical elements, creating advantages over opponents and influencing the overall dynamics and outcome of the game. Linear sprint (LS) (e.g., maximal-effort sprint acceleration) and forward movements are frequently used activities by the athlete before scoring a goal, providing a convenient position for the shot, the ball's trajectory and greater speed in the decisive moments of the game (Faude et al., 2012; Martínez-Hernández et al., 2023). LS is one of the most assessed components in field-based team sports (Simperingham et al., 2016). In outdoor team sports, athletes perform LS up to 20 m or an average of 2 to 4 seconds (Spencer et al., 2005) and mostly do not reach maximal velocity during the game. Thus, the activity profile mostly consists of accelerations (Sweeting et al., 2017), recommending to include <20 m LS in testing protocols for team sports (Simperingham et al., 2016). However, in indoor team sports, accelerations are mostly performed over shorter distances (<10 m), emphasising the horizontal-oriented ground reaction force generation efficiency (Bezodis et al., 2017). Overall, athletes in game perform not only LS but implementing more curvilinear sprint (CS) and changes of direction (COD) manoeuvres to achieve the goal of the movement (Conte et al., 2015; Fitzpatrick et al., 2019). Therefore, understanding the associations between multi-directional speed movements enables practitioners to more effectively optimise athlete performance and design targeted and sport-specific training interventions.

In team sports, athletes must adapt to the contextual situations of the game, such as avoiding opponents, intercepting the ball, or creating space for offensive and defensive manoeuvres, implementing CS as a technical skill. According to Filter et al. (2020a), CS can be defined as the “*athlete's ability to sprint in a curved trajectory with a certain degree of curvature and a continuous change of direction, without a deceleration phase, and generating centripetal forces that provide the movement along a curved trajectory.*” Caldbeck & Dos Santos (2022) reported that approximately 85% of maximum speed sprints and manoeuvres in football are completed with some degree of curvature (e.g., curvilinear trajectory). However, in elite women's basketball, 31% of all sprints performed are curvilinear (Conte et al., 2015). Thus, both the frequency and radius of CS execution may differ between outdoor and indoor sports. For example, in soccer radii typically range from 3.5 m to 11 m (Brice et al., 2008), with angles of approximately 6.2° and, in some cases, even up to 30° (Fitzpatrick et al., 2019), whereas there is limited evidence about indoor team sports. Moreover, biomechanical differences between the inside and outside limbs indicate an asymmetric force-generating mode (Judson et al., 2020). CS requires specific neuromuscular (e.g., outside and inside limb muscle activation, strength, reactivity, and stiffness), kinematic and kinetic (e.g., body position, ground reaction force application, and joint angles), and spatiotemporal (e.g., contact time, stride length and frequency) adaptations, as it is a different physical skill from LS (Filter et al., 2020a). In addition, previous studies have documented slightly faster CS performance with the left limb inside (Filter et al., 2020b; Sašek et al., 2024). Overall, CS has a similar and, at the same time, a different movement pattern than LS, demonstrating a moderate to large association between components (Filter-Ruger et al., 2022); thus, athletes generally execute CS slower than LS (Baena-Raya et al., 2023; Loturco et al., 2020). In recent years, the difference between CS and LS can be calculated as a curvilinear deficit (CSD), where a lower CSD reflects an athlete's ability to effectively adapt to biomechanical and postural demands without a reduction in sprint velocity (Loturco et al., 2020). Although athletes may perform CS more frequently than LS in game scenarios, there is limited evidence regarding whether CSD increases, stabilises, or decreases over longer distances, as well

as about cases when an athlete executes CS faster or in equal time as LS. A faster CS performance could indicate an athlete's higher technical ability compared to isolated LS.

During game, athletes must effectively accelerate, decelerate, execute cuts, and repeatedly accelerate from different angles and positions of the body to minimise the risk of injuries (Nimphius et al., 2018). Bloomfield et al. (2007) emphasise that in a football game, an athlete performs more than 700 changes of direction, of which 300 are within 90°, forty-five from 90° to 180°, three from 180° to 270°, but only one from 270° to 360°. In contrast, Sweeting et al. (2017) report that the COD most frequently occur at angles between 45° and 90°. However, in basketball, athletes change direction every one to three seconds (Conte et al., 2015; Stojanović et al., 2018), executing over 300 COD manoeuvres during the game (Svilar & Jukić, 2018). Since the CODs are angle-dependent abilities, the different testing strategies provide coaches with precise tools to assess and monitor performance. For example, utilising tests that minimise the impact of acceleration on overall COD performance, such as the modified 505 test (e.g., 180° COD) (Ryan et al., 2022), practitioners can assess isolated strength-based COD performance. However, the 45° COD is characterised by a continuous running scenario similar to CS; therefore, it is defined as velocity-based COD (Bourgeois et al., 2017). In-game, athletes are required to perform COD effectively using both the right and left limbs as a plant foot; however, previous studies show that athletes tend to execute faster COD with one limb as a dominant limb (Arboix-Alió et al., 2021; Bishop et al., 2021). Furthermore, similar to CS, in COD tasks, practitioners can indicate the COD deficit (CDD), or the additional time required to make a COD compared to LS at an equivalent distance (Nimphius et al., 2013). Previous studies (Lazić et al., 2023; Pereira et al., 2018) report that athletes who show faster LS results often perform COD slower; therefore, CDD values are also higher. Although 180° and 45° COD have different biomechanical and neuromuscular demands, there is limited evidence about the association with CS and CSD. By identifying associations between multi-directional speed components and deficits, especially assessing the performance of the inside and outside (e.g., right and left) limbs, practitioners could gain useful information about possible lower limb dominance and mechanical differences and advantages in floorball (Loturco et al., 2020; Sašek et al., 2025).

Therefore, to investigate the multi-directional speed abilities of floorball players, the first study aim is to determine the performance of floorball players in CS, COD and LS, as well as CS and COD deficit values when distance length increases from both right and left limbs. This provides the opportunity to determine whether deficits increase, stabilise, or decrease over longer distances. However, the second aim of the study is to investigate the associations between CS and LS and velocity-based and strength-based COD performance variables, such as times and deficits. We hypothesised that deficits are higher as the distance increases, expecting that there is a significant association between CS and other multi-directional speed variables.

MATERIALS AND METHODS

Design and procedure

A cross-sectional study design was used to investigate floorball players' LS, CS, and COD, as well as deficits. Data were collected from two separate testing days (each lasting approximately 80 min). During the first visit, the anthropometric measurements (height, weight and body mass index) were obtained, as well as participants performed 20 m LS and CS tests. However, during the second visit, participants performed COD tests (180° and 45° Y-shape COD tests). All participants were in their regular competitive period during data collection. The test procedures took place in natural settings, e.g., on a floorball synthetic surface, at the participants' training base, during training time. Before the testing, in both visits, participants completed the same standard warm-up consisting of muscle activation, dynamic lower-limb stretching exercises, and sprint

drills. Sprint and COD tests results were obtained using Microgate Witty (Microgate Srl, Bolzano, Italy) photocells to the nearest 0.01 seconds (Colino et al., 2019). The photocell pair was placed 1.5 m away, facing each other on marked points (Baena-Raya et al., 2023). Before each test, participants completed two submaximal trials at 60 to 80% of maximum intensity as familiarisation trials. The study received ethical approval (71-43/159) from the local ethics board and followed strict principles set in the World Medical Association Declaration of Helsinki.

Participants

The sample size was calculated using G*Power software (version 3.1.9.6, Kiel, Germany) for correlation analysis, based upon an effect size of 0.4 with a statistical power of 0.80 and an alpha error probability of .05, indicating that the minimal sample size is 34 floorball players. Therefore, forty eight male floorball players (age: 18.0 ± 3.7 years; body height: 180.8 ± 6.5 cm; body mass: 74.9 ± 8.6 kg; body mass index: 22.97 ± 2.3) participated in this study. All players were healthy and reported no musculoskeletal or neuromuscular injuries, health problems or pain syndromes in the past six months that could affect the results or the subjects' overall physical and psychological health. Participants were informed about the research protocol, benefits and risks. A written informed consent form was signed and obtained before tests.

Linear sprint tests

A 20 m sprint test was utilised to assess the floorball players' LS performance. All participants were instructed to stand in a two-point start position with the front limb 0.3 m behind the starting line and perform three maximal 20 m LS trials with two to three minutes of recovery between trials. Sprint distance was divided into four phases (0–5 m; 5–10 m; 10–15 m; 15–20 m), using five photocell pairs that collected split times. The best recorded 20 m sprint time, as well as trial split times were used for data analysis.

Curvilinear sprint test

The 20 m 3-point line arch test was used to assess CS performance. In basketball players, the test has demonstrated high reliability (CV, 5%; ICC ≥ 0.90). (Baena-Raya et al., 2023). According to International Basketball Federation (FIBA) regulations, the official curve radius for the 3-point line is 6.75 metres with an amplitude of 10.58° from the floor beneath the precise centre of the basket to the outside border of the arch. The test procedure took place in a multifunctional hall featuring a basketball court marked according to FIBA regulations, allowing the test to be used in other team sports, such as floorball. Using a tape measure, the 3-point line was precisely extended to match the 20 m length. In previous studies, such as by Baena-Raya et al. (2023), CS times were assessed from 0 to 18.7 m without split times, but Pleša et al. (2025) utilised a 20 m CS test. As a result, our study includes 20 m CS with split times, which provide a more precise assessment of an athlete's curvilinear sprint abilities, particularly since the first metres in team sports are crucial. The CS test was divided into phases (0–5 m, 5–10 m, 10–15 m, 15–20 m), using five photocell pairs that collected split times. All participants were instructed to stand in a two-point start position with the front limb 0.3 m behind the starting line and perform three maximal CS efforts with the right limb inside and three with the left limb inside, without crossing the line. During the testing process, an experienced research assistant monitored the participants' performance to ensure that the sprint was executed correctly. The best recorded 20 m CS trial from both sides, as well as trial split times were used for data analysis.

Modified 505 test (180° COD)

The modified 505 m test was used to assess the participant's isolated COD speed, which is commonly observed in practice as a strength-based test. The athlete's 180° cut strategy has been significantly observed in team sports, such as soccer (Kadlubowsk et al., 2019), basketball (Baena-Raya et al., 2023; Spiteri et al., 2019), and floorball (Leppänen et al., 2021). Stojanović et al. (2019) reported that the test showed high

reliability (ICC = 0.82; CV% < 5.1%) to assess the isolated COD speed performance that is unaffected by acceleration ability or anaerobic capacity. All participants were instructed to stand in a two-point start position 0.3 m from the starting line (first photocell pair). Then accelerate 5 m to a COD line, place either the right or left lower limb on the line, depending on the attempt, turn 180° on either the right or left lower limb, and sprint back 5 m through the finish. The experienced research assistant ensured that the participant's turning limb was on the line (Baena-Raya et al., 2023; Taylor et al., 2019). If the participant turned before the line or used an incorrect turning limb, the trial was not considered successful. Each participant performed three COD trials on each limb, with a two to three min recovery between each trial. The best 180° COD trial for each limb were used for data analysis.

Y-shape 45° change of direction test (45° COD)

To assess the velocity-based change of direction, the Y-shaped test was used (Fiorilli et al., 2017). Several studies have shown that the Y-shape test is reliable and valid for measuring athletes planned COD and reactive agility (Horníková & Zemkov, 2022; Oliver & Meyers, 2009). During test preparation, the COD line was measured 5 meters from the start line. However, the finish line was measured 5 meters from the COD line to the right and left sides at a 45° angle. Using a goniometer, it was determined that the 45° angle is exactly in the middle of the COD and finish lines. Time gates were placed at each marked point. Each participant was instructed to stand in a two-point start position 0.3 m from the starting line, and after receiving approval, perform a 5 m maximal effort acceleration, change direction at a 45° angle as quickly as possible, placing either the right or left lower limb on the COD line depending on the attempt, and sprint 5 m through the finish. The experienced research assistant ensured that the participant's turning limb was on the line. If the participant turned before the line or used an incorrect turning limb, the trial was not considered successful. Each participant performed three attempts on each limb, with a two to three minute recovery between each trial. The best 45° COD trial for each limb, as well as trials split times, were used for data analysis.

Statistical analysis

Data were compiled in Microsoft Excel 2025 and analysed in IBM SPSS (Statistical Package for the Social Sciences) Statistics 29 (version: 29.0.0.0 (241)). All descriptive data were presented as means $\pm$ standard deviations, range (min and max), 95% lower–upper confidence intervals and a difference between limbs. The Shapiro-Wilk test was utilised to determine the normality of the data. A paired-sample t-test was performed to determine differences between right and left limbs in CS, 45° COD, and 180° COD test variables. The Pearson correlation coefficient (r) was utilised for parametric data, and the Spearman rank correlation coefficient (ρ) for non-parametric data. Correlations are classified as follows: trivial (<0.1), small (0.1–0.3), moderate (0.3–0.5), large (0.5–0.7), very large (0.7–0.9), and perfect (1). The significance level for all statistical tests was set to .05 (Hopkins et al., 2009). CSD and CODD were calculated as the time difference between CS or COD and LS (Loturco et al., 2020; Nimphius et al., 2013).

RESULTS

The Shapiro-Wilk test of normality revealed that all performance variables were normally distributed ($p < .05$), except for the 180° CODD from both limbs ($p > .05$). Table 1 presents the mean results for performance total and split times for the LS, CS, and COD tests, along with minimal and maximal times and the 95% confidence intervals. On average, athletes demonstrated faster sprint times in LS compared to CS; however, some athletes achieved faster times in the first 5 m of 45° COD and CS compared to the first 5 m of LS. In addition, athletes demonstrated faster times in CS with the left limb positioned inside. However, 180° COD performance revealed an opposite trend, with athletes achieving faster times when changing direction with

the right limb. Significant differences between limbs were observed in CS (5, 10 and 15 m) and 180° COD 10 m times ($p < .05$), while no differences were found in any 45° COD variables ($p > .05$).

Table 1. Descriptive analysis (Mean $\pm$ SD), range (min–max), 95% confidence intervals (CI) and limb differences of the curvilinear sprint, change of direction and linear sprint tests performance variables.

Variables	Mean $\pm$ SD	Range (Min–Max)	95% lower – upper CI	p-value
LS 5 m (s)	1.04 $\pm$ 0.06	0.95 – 1.18	1.02 to 1.06	<.001
LS 10 m (s)	1.76 $\pm$ 0.08	1.63 – 1.94	1.74 to 1.79	
LS 15 m (s)	2.43 $\pm$ 0.11	2.23 – 2.69	2.04 to 2.47	
LS 20 m (s)	3.04 $\pm$ 0.13	2.84 – 3.35	3.00 to 3.08	
CS R 5 m (s)	1.07 $\pm$ 0.06	0.97 – 1.19	1.05 to 1.09	.003
CS L 5 m (s)	1.05 $\pm$ 0.06	0.94 – 1.19	1.03 to 1.07	
CS R 10 m (s)	1.83 $\pm$ 0.07	1.71 – 1.97	1.81 to 1.86	.019
CS L 10 m (s)	1.81 $\pm$ 0.09	1.66 – 2.00	1.78 to 1.83	
CS R 15 m (s)	2.57 $\pm$ 0.12	2.36 – 2.88	2.54 to 2.61	.002
CS L 15 m (s)	2.53 $\pm$ 0.13	2.34 – 2.88	2.49 to 2.56	
CS R 20 m (s)	3.24 $\pm$ 0.13	3.02 – 3.55	3.21 to 3.28	.878
CS L 20 m (s)	3.24 $\pm$ 0.14	2.95 – 3.54	3.20 to 3.29	
180° COD R 10 m (s)	2.50 $\pm$ 0.15	2.28 – 2.88	2.46 to 2.55	.002
180° COD L 10 m (s)	2.55 $\pm$ 0.14	2.31 – 2.89	2.51 to 2.60	
45° COD R 5 m (s)	1.06 $\pm$ 0.08	0.92 – 1.27	1.04 to 1.08	.495
45° COD L 5 m (s)	1.06 $\pm$ 0.07	0.93 – 1.24	1.03 to 1.08	
45° COD R 10 m (s)	1.80 $\pm$ 0.11	1.64 – 2.07	1.77 to 1.83	.192
45° COD L 10 m (s)	1.79 $\pm$ 0.10	1.64 – 2.10	1.76 to 1.82	

Note. LS: linear sprint; CS: curvilinear sprint; COD: change of direction; R: right limb; L: left limb.

Although the mean CSD and CODD values are positive (e.g., athletes perform LS faster), in some cases athletes have shown faster results in CS and 45° COD tasks (Table 2). Overall, as the distance length increases, the deficit value also increases, indicating task specific demands. Significant differences between limbs were observed in CSD (5, 10 and 15 m) and 180° CODD 10 m times ($p < .05$), while no differences were found in any 45° CODD variables ($p > .05$).

Table 2. Descriptive analysis (Mean $\pm$ SD), range (min–max), 95% confidence intervals (CI) and limb differences of the curvilinear sprint and change of direction deficits.

Variables	Mean $\pm$ SD	Range (Min–Max)	95% lower – upper CI	p-value
CSD R 5 m (s)	0.04 $\pm$ 0.05	-0.03 – 0.14	0.03 to 0.06	.003
CSD L 5 m (s)	0.02 $\pm$ 0.03	-0.04 – 0.11	0.01 to 0.03	
CSD R 10 m (s)	0.08 $\pm$ 0.06	-0.01 – 0.21	0.06 to 0.10	.019
CSD L 10 m (s)	0.05 $\pm$ 0.06	-0.04 – 0.22	0.04 to 0.07	
CSD R 15 m (s)	0.15 $\pm$ 0.09	-0.01 – 0.39	0.12 to 0.17	.002
CSD L 15 m (s)	0.10 $\pm$ 0.08	-0.03 – 0.34	0.08 to 0.13	
CSD R 20 m (s)	0.21 $\pm$ 0.09	0.00 – 0.44	0.18 to 0.24	.878
CSD L 20 m (s)	0.21 $\pm$ 0.10	0.00 – 0.52	0.18 to 0.24	
180° CODD R 10 m (s)	0.75 $\pm$ 0.11	0.58 – 1.13	0.72 to 0.78	.002
180° CODD L 10 m (s)	0.79 $\pm$ 0.12	0.55 – 1.15	0.76 to 0.83	
45° CODD R 5 m (s)	0.03 $\pm$ 0.04	-0.04 – 0.20	0.02 to 0.04	.495
45° CODD L 5 m (s)	0.03 $\pm$ 0.05	-0.04 – 0.16	0.01 to 0.04	
45° CODD R 10 m (s)	0.05 $\pm$ 0.05	-0.02 – 0.19	0.03 to 0.06	.192
45° CODD L 10 m (s)	0.04 $\pm$ 0.05	-0.03 – 0.19	0.02 to 0.05	

Note: CSD: curvilinear sprint deficit; CODD: change of direction deficit; R: right limb; L: left limb.

As statistical differences were observed between limbs, a correlation analysis was performed between all performance variables of each limb, including LS. Therefore, CS and CSD correlations with 45° COD, 45° CODD, 180° COD, 180° CODD and LS variables for the right limb are shown in Table 3, and for the left limb in Table 4. The significant positive correlations were observed between right and left limbs CS times and 45° COD times ($r = 0.55$ to 0.81 , $p < .01$), 180° COD time ($r = 0.34$, $p < .05$ to 0.61 , $p < .01$) and LS times ($r = 0.60$ to 0.82 , $p < .01$). Right limb 20 m CS time showed positive moderate correlation with 5 m 45° CODD ($r = 0.30$, $p < .05$) and 10 m 45° CODD ($r = 0.38$, $p < .01$), as well as 180° CODD ($r = 0.42$, $p < .01$) (Table 3). However, left limbs 20 m CS time showed a significant correlation only with 180° CODD ($r = 0.31$, $p < .05$) (Table 4).

There were negative moderate correlations between 10 m CSD and 45° COD times, 180° COD time and LS times ($r = -0.30$, $p < .05$ to -0.50 , $p < .01$), whereas left limb 5 m CSD showed only a positive moderate correlation with 45° CODD ($r = 0.31$ to 0.33 , $p < .05$) and negative with LS 5 m time ($r = -0.32$, $p < .05$). However, right limbs 20 m CSD was a moderate negative correlation with 180° COD 10 m time ($r = -0.34$, $p < .05$) and LS 20 m time ($r = -0.38$, $p < .01$), as well as 5 m CSD with LS 5 m time ($r = -0.37$, $p < .01$) and 15 m CSD and 15 m LS time ($r = -0.31$, $p < .05$).

Table 3. Correlation coefficients between curvilinear sprint and change of direction and linear sprint performance variables for the right limb.

		CS performance times				CS deficits			
		5 m	10 m	15 m	20 m	5 m	10 m	15 m	20 m
45° COD	5 m	0.55**	0.70**	0.72**	0.72**	-0.31*	-0.35*	-0.10	-0.17
	10 m	0.61**	0.70**	0.74**	0.79**	-0.26	-0.36*	-0.09	-0.13
	CODD 5 m	0.06	0.20	0.26	0.30*	-0.03	-0.06	-0.04	0.04
	CODD 10 m	0.20	0.20	0.30*	0.38**	0.07	0.08	0.15	0.25
180° COD	10 m	0.36*	0.34*	0.45**	0.46**	-0.21	-0.46**	-0.10	-0.34*
	CODD 10 m	-0.01s	-0.10s	0.02s	0.42s**	0.06s	-0.24s	0.05s	-0.20s
LS	5 m	0.68**	0.73**	0.75**	0.75**	-0.37**	-0.39**	-0.11	-0.26
	10 m	0.63**	0.74**	0.73**	0.74**	-0.35*	-0.50**	-0.21	-0.30*
	15 m	0.60**	0.64**	0.73**	0.81**	-0.33*	-0.42**	-0.31*	-0.32*
	20 m	0.64**	0.74**	0.75**	0.74**	-0.30*	-0.41**	-0.21	-0.38**

Note: LS: linear sprint; CS: curvilinear sprint; COD: change of direction; CSD: curvilinear sprint deficit; CODD: change of direction deficit, * $p < .05$, ** $p < .01$, s Spearman rho (ρ) correlation coefficient.

Table 4. Correlation coefficients between curvilinear sprint and change of direction and linear sprint performance variables for the left limb.

		CS performance times				CS deficits			
		5 m	10 m	15 m	20 m	5 m	10 m	15 m	20 m
45° COD	5 m	0.73**	0.67**	0.65**	0.64**	-0.06	-0.06	0.02	-0.05
	10 m	0.81**	0.76**	0.72**	0.72**	0.01	-0.06	-0.01	-0.06
	CODD 5 m	0.09	0.11	0.08	0.08	0.31*	0.21	0.14	0.12
	CODD 10 m	0.23	0.16	0.14	0.19	0.33*	0.28	0.16	0.17
180° COD	10 m	0.56**	0.58**	0.53**	0.61**	0.06	0.07	0.13	0.06
	CODD 10 m	0.15s	0.18s	0.19s	0.31s*	0.21s	0.11s	0.13s	0.15 s
LS	5 m	0.82**	0.73**	0.73**	0.71**	-0.32*	-0.24	-0.08	-0.15
	10 m	0.82**	0.79**	0.76**	0.73**	-0.21	-0.25	-0.11	-0.19
	15 m	0.72**	0.77**	0.80**	0.75**	-0.26	-0.19	-0.15	-0.17
	20 m	0.78**	0.76**	0.78**	0.74**	-0.20	-0.22	-0.11	-0.26

Note: LS: linear sprint; CS: curvilinear sprint; COD: change of direction; CSD: curvilinear sprint deficit; CODD: change of direction deficit, * $p < .05$, ** $p < .01$, s Spearman rho (ρ) correlation coefficient.

DISCUSSION

The present study aimed to determine floorball players' performance in CS, COD and LS, as well as CS and COD deficit values when distance length increases, and to investigate the associations between CS performance and LS and velocity-based and strength-based COD variables. The main study findings were: (a) on average, floorball players performed 10 m CS and 45° COD slower than 10 m LS, showing greater CSD and 45° CODD as the distance length increased; however, in some cases, athletes performed slightly faster CS and 45° COD, indicating technical ability over isolated LS performance; (b) there are significant statistical differences between the right and left limb performance times in CSD (5 m, 10 m and 15 m) and 180° CODD; (c) CS times showed moderate to very large correlation with 45° COD, 180° COD and LS times; however, moderate correlations were determined between left limb 5 m CSD and 45° CODD 5 m and 10 m. Although athletes performed CS faster when the left limb was inside, only the right limb CSD had a statistically significant negative correlation with the multi-directional speed component times. Our hypothesis was confirmed, indicating that as CS and COD distances increased, deficit values also increased. The present study is the first to reveal cases where an athlete performs CS and 45° COD slightly faster, especially in the first 5 m (Table 1). These findings provide useful information to practitioners, indicating significant associations between CS and 45° COD and both components as a technical skill in floorball.

Previous studies in team sports have documented significant differences in CS performance between the right and left limbs (e.g., curve sprint good and weak side) (Baena-Raya et al., 2023; Filter et al., 2020a; Filter et al., 2020b; Filter et al., 2025; Loturco et al., 2020). Team sports are often referred to as “*asymmetrical*”, as athletes frequently prefer to use one lower limb or side of the body in sport-specific movements (i.e., cutting, kicking, jumping, sprinting, and changing direction), leading to the development of neuromuscular asymmetry and side-specific adaptations (Fort-Vanmeerhaeghe et al., 2015; Maloney, 2019). For instance, longer contact time, stride length, and flight time, as well as lower stride frequency, vertical and propulsive forces, and higher braking forces, have been previously observed in the CS inside limb compared to the outside limb (Smith et al., 2006). In the present study, on average, athletes achieved faster 15 m CS times with the left limb positioned inside (2.53 ± 0.13 s) versus the right limb (2.57 ± 0.12 s). However, there are no significant differences in the CS time between the right and left limbs at 20 m. Since the floorball sprint profile is based on short accelerations, when distance length increases in CS, athletes may have difficulty resisting centripetal force, creating several mechanical adjustments in sprint pattern, which cause a decrease in velocity. The opposite scenario was observed in 180° COD, where floorball players performed faster COD when final foot contact (plant step) was with the right limb (2.50 ± 0.15 s) rather than with the left limb (2.55 ± 0.14 s). Similar results were reported by Cuthbert et al. (2019) using the 505 test (15 m + 5 m), where male team sport athletes performed faster COD with the right limb. However, authors utilised the COD test with a longer acceleration phase (e.g., athletes developed higher LS velocity); therefore, COD times were faster, and the CODD values were smaller, as opposed to the present study, which included isolated COD speed assessment. Overall, Filter et al. (2021) report that most soccer players showed asymmetry in one direction during the COD test and in the other during the CS test, emphasising the different roles of each limb and supporting the present study's results. In fact, during CS, the inside limb plays a crucial role in forward propulsion, whereas the outside limb has a greater contribution in COD tasks (Filter et al., 2020b). However, floorball players performed 45° COD similarly with both the right and left limbs (10 m: 1.80 ± 0.11 s and 1.79 ± 0.10 s, respectively). A possible explanation could be that the 45° COD involves a relatively small change of direction; therefore, the plant limb is not crucial as in 180° COD (Horníková & Zemková, 2022). These findings suggest that CS and COD are different physical qualities in terms of directional dominance that need to be developed and monitored separately to improve overall performance in floorball.

A large to very large correlation was observed between CS and LS performance times for both limbs ($r = 0.60$ to 0.82 , $p < .01$), suggesting that athletes who showed faster LS times tend to sprint fast also in CS. However, a higher correlation coefficient was identified with left limb CS, possibly due to more efficient force generation, body positioning, joint stabilisation in the frontal plane and a higher ability to use linear velocity, indicating potential limb dominance. Loturco et al. (2020) also reported a large to very large correlation ($r = 0.52$ to 0.82) between CS and LS velocities, indicating that CS performance is influenced by LS ability. Furthermore, only a few previous studies have examined associations between CS and COD. For example, Freitas et al. (2020) identified a large correlation with COD from the Zigzag test ($r = 0.54$ to 0.60 , $p < .05$), while Fíler et al. (2021) reported a moderate relationship between CS and the 90° COD test ($r = 0.33$ to 0.41 , $p < .05$). However, the present study identifies a novel perspective on 45° COD and CS as velocity-based abilities that have similar biomechanical requirements; therefore, a moderate to very large correlation was indicated, especially for the left limb performance times ($r = 0.72$ to 0.81 , $p < .01$). Additionally, the significant moderate correlations between CS and 180° COD times were also observed, ranging from $r = 0.34$ to 0.36 ($p < .05$) for the right limb and $r = 0.56$ to 0.58 ($p < .01$) for the left limb. Although CS cannot be classified as a COD, both components share common whole-body movement strategies and biomechanical features (i.e., body lateral inward lean and asymmetrical mediolateral ground reaction forces), particularly at narrower COD angles. These similarities can be a potential reason for the observed significant association with COD performance (Freitas et al., 2021; Kobal et al., 2021).

Another relevant finding was that floorball players both right and left limb CSD deficits gradually increased up to 15 m but stabilised at 20 m, suggesting a potential limb difference plateau over longer distances. The deficit correlation analysis indicates that the right limb 5 m or 10 m CSD values were negatively associated with 45° COD times (5 m and 10 m) and 180° COD 10 m time, indicating a possible movement strategy trade-off. Athletes who are able to perform fast CS (i.e., demonstrated lower CSD values) may lack efficiency in the COD tasks, especially with the right limb and the plant limb. One possible reason may be that in CS athletes perform cyclic and continuous sprint steps, whereas in COD the athlete often adjusts the steps prior to the plant phase to perform a cutting manoeuvre (Dos'Santos et al., 2018). Notably, no significant association was found between CSD and COD times with the left limb, suggesting limb-specific asymmetries and dominance. Furthermore, with all deficits, only 5 m CSD shows positive correlation with 45° COD (both 5 m and 10 m) ($r = 0.31$ to 0.34 , $p < .05$); thus, athletes who are less efficient in utilising LS abilities in the initial CS also tend to show greater inefficiency in 45° COD. These findings open new directions of research, where further studies are required that clarify a more detailed explanation of limb dominance, performance efficiency, and the association with CSD in different sports. It should be noted that in this study, there are cases where athletes performed CS or 45° COD slightly faster than LS (Table 1). In floorball, athletes perform CS or COD manoeuvres more often than isolated LS, thereby integrating these components into tactical situations of the game and improving them as a technical skill. This is especially observed in the first 5 m of both CS and 45° COD. To achieve maximum sprint speed in LS, the athlete must perform a gradual increase in step length and frequency, which requires high levels of coordination and horizontal ground reaction force generation. However, higher step frequency has been reported in team sports, where shorter first sprint steps and shorter flight time could be beneficial for efficient performance (Murphy et al., 2003; Sayers, 2000). Therefore, in some cases, the athlete performed the initial phase faster than LS. In semi-professional soccer players, Fíler et al. (2020b) observed a similar trend, where higher velocities were achieved in CS from the “good” side than in LS. As previously mentioned, performance technique and potential sport-specific characteristics (i.e., court surface, playing position and level) as well as radius length can significantly influence speed development. Therefore, understanding sport-specific characteristics enables practitioners to design tailored training interventions, thereby providing athletes with an advantage over their opponents.

The main limitation of this present study is the cross-sectional design, indicating only associations between multi-directional speed components and deficits. In addition, only representatives from one team sport and nation were included in this study. Overall, future studies should examine deficits at other COD angles, such as 90° or 135°, as well as utilise CS with different radii to identify both radius and angle biomechanical and neuromuscular requirements. To determine if performance times and deficits change (i.e., increase, stabilise or decrease) throughout a season or with the integration of specific training methods, longitudinal studies are needed to determine benchmarks for each cohort to identify poor and good performance.

CONCLUSIONS

In conclusion, this present study investigates the multi-directional speed performance in floorball players and associations between CS and LS and angle-dependent COD, identifying deficits and possible limb dominance. On average, floorball players tend to perform the initial phase of LS faster than CS and COD, but in some cases, athletes demonstrate faster results, especially in the first 5 m. As the CS time improves, athletes also perform LS and COD faster, highlighting the multi-directional speed competence of floorball players. Floorball players who demonstrate fast CS with the right limb inside tend to lack efficiency in the COD tasks with the same limb. However, athletes who tend to be less efficient at utilising LS abilities in the initial CS also show greater inefficiency in 45° COD, especially with the left limb. These findings suggest that CS and 45° COD are velocity-based abilities that have similar biomechanical requirements, as well as lower limb dominance in floorball. Therefore, practitioners and coaches can benefit from the integration of different multi-directional strategies effectively to develop faster CS in floorball players.

AUTHOR CONTRIBUTIONS

LV – study design, data curation, writing – original draft, review and editing; LP – conceptualization of the study, writing – review and editing; IA – study design, data curation, writing – review and editing.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

DATA AVAILABILITY

Data will be available upon request to the corresponding author.

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