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Field Position- and Training Age-Related Differences in Motor-Cognitive Abilities of 10–17-Year-Old Soccer Players

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Abstract

In team sports such as soccer, players must rapidly and accurately process dynamic visual scenes based on the real-time movements and positioning of teammates and opponents. This study aimed to investigate differences in brain processing speed, cognitive agility, and lower-limb reactive agility among youth soccer players aged 10–17 years, considering both field position and level of playing experience. A total of 142 male players (mean age 13.27 ± 2.35 years) were assessed and categorized according to their training age and field position. Brain processing speed and cognitive agility were measured using the Witty SEM system with the BrainHQ Hawk Eye and BrainHQ Agility tests, while lower-limb reactive agility was evaluated via the Fitro Agility Check. Players with 7–9 years of training experience achieved significantly faster brain speed reaction times (BSRT; $p=0.013$, $\eta^2=0.076$) and lower complex disjunctive reaction times (CDR; $p<0.001$, $\eta^2=0.340$) compared with players with 1–3 years of experience. Large training-age effects were also found in all agility directions ($\eta^2=0.277$ – 0.385). These findings demonstrate that greater sport experience is strongly associated with enhanced perceptual-cognitive and motor-reactive efficiency in youth soccer.

Keywords: brain speed quality, cognitive agility, lower-limb reactive agility, training age, field position, soccer

Introduction

Recent studies consistently highlight the strong interconnection between cognitive and motor functions in the context of youth sports performance. Cognitive domains such as attention, working memory, and executive control are closely tied to sport-specific skills including dribbling, ball control, and reaction speed (Scharfen & Memmert, 2019; Trecroci et al., 2021). Evidence indicates that athletes who exhibit higher proficiency in these cognitive areas tend to achieve superior results in tasks requiring rapid motor execution. Interventions that combine physical and cognitive demands—particularly dual-task cognitive-motor training—have been shown to improve both domains concurrently, enhancing anticipatory decision-making under pressure and refining athletes' ability to adapt their actions to rapidly changing game environments (Friebe et al., 2024; Lucia et al., 2024).

Such approaches are particularly relevant in soccer, where the constant flow of play demands simultaneous pro-

cessing of sensory information and rapid motor responses. Decision-making in soccer relies heavily on the integration of perceptual input, memory recall, and accumulated tactical knowledge. Players must rapidly interpret visual cues such as the relative positions of teammates and opponents, available space, and movement trajectories to anticipate game developments and select appropriate motor actions (Habekost et al., 2024; Rodrigues et al., 2022). As experience increases, these processes become more automated and parallel in nature, allowing players to recognize familiar patterns and retrieve effective motor strategies with greater speed and accuracy (Ramsey et al., 2024). This shift from serial to parallel processing represents a hallmark of expertise in soccer and is strongly influenced by both the quality and quantity of training.

Training formats such as small-sided games and game-based dual-task exercises have been found to strengthen attention, situational awareness, and action selection, all while exposing players to match-like time constraints and unpredictability (Machado et al., 2024). Perceptual-cognitive

skills—including decision-making speed, anticipation, and visual reaction time—are also fundamental determinants of agility and reactive movement performance in soccer. These skills enable players to detect, interpret, and respond to game-relevant stimuli in a fraction of a second, which is critical during dynamic, high-intensity situations (Demir & Kiyici, 2023; Horníková et al., 2024). In adolescent athletes, reactive agility has been shown to be significantly influenced by cognitive processing efficiency, particularly in scenarios that require rapid directional changes in response to unpredictable stimuli. Integrative training methods, in which sprinting, change-of-direction, and decision-making tasks are combined, have been demonstrated to yield improvements in both the physical and cognitive determinants of agility (Friebe et al., 2024). These findings support the use of multifactorial training programs that simultaneously target perceptual-cognitive and motor capacities in youth soccer development.

Training experience and sport-specific age emerge as key determinants of cognitive-motor efficiency. Players with greater exposure to structured soccer training typically show faster reaction times, superior attentional control, and more accurate decision-making under visually complex conditions (Klatt et al., 2021). Long-term engagement in sport appears to accelerate the development of neural pathways involved in rapid information processing and motor execution. Age-related improvements in agility, decision accuracy, and processing speed reflect the combined effects of biological maturation and accumulated sport-specific practice (Andrašić et al., 2021). Evidence suggests that implementing small-sided games and perceptual-cognitive drills at an early age may foster these developmental gains, particularly in enhancing players' ability to perform under cognitive and physical load (Machado et al., 2024).

Taken together, the literature demonstrates that both sport-specific experience and age contribute to improvements in perceptual-cognitive and motor skills in soccer. Experienced players generally display more efficient visual processing, quicker reaction times, and better tactical decision-making under pressure, reflecting the integration of accumulated playing knowledge with refined attentional control (Klatt et al., 2021). These developmental and experiential trends justify systematic comparisons of brain speed, disjunctive reaction time, and directional agility across different levels of training age and playing positions. The present study extends previous research by examining two major developmental determinants, training age and field position, within a single design. Earlier studies focused on these factors separately, while our approach provides an integrated view of how motor-cognitive abilities evolve across both. Identifying interactions between experience and positional demands offers new insights into evidence-based and position-specific training in youth soccer.

Materials and methods

Participants and design

This study was conducted as a four-group, two-factor, non-randomized cross-sectional design. A total of 142 male soccer players aged 10 to 17 years (mean age = 13.27 ± 2.35

years) participated in the research. Participants were categorized based on two independent grouping factors: training experience (training age) and field position. Training age was defined as the total number of completed years of organized soccer participation under qualified coaching supervision. Players were divided into four training-age groups TA1–3 years ($n=25$, $M=10.7 \pm 1.2$), TA4–6 years ($n=48$, $M=11.8 \pm 0.8$), TA7–9 years ($n=49$, $M=14.6 \pm 0.8$), and TA10–13 years ($n=20$, $M=16.7 \pm 0.9$) based on total years of experience. All participants competed in the same official youth categories according to their chronological age, which minimized biological-maturity differences across groups. Field position categories included defenders ($n=57$, $M=13.1 \pm 0.5$), strikers ($n=43$, $M=13.2 \pm 2.3$), midfielders ($n=30$, $M=13.2 \pm 2.4$), and goalkeepers ($n=12$, $M=14.5 \pm 2.2$).

Procedures

Testing took place during the competitive season, when all players were actively involved in structured training 3 to 4 times per week and one competitive match each weekend, resulting in a total weekly training volume of approximately 6 to 8 hours. Motor-cognitive performance was assessed using the Witty SEM diagnostic system (Andrašić et al., 2021; Vasile et al., 2024). Cognitive agility was measured by the BrainHQ Agility Test, in which the participant's task was to respond as quickly as possible to a green lowercase letter "a" appearing randomly among eight semaphores, while ignoring distractors composed of various letters and numbers displayed in other colors. Brain speed was measured using the BrainHQ Hawk Eye Test (also referred to as the Peripheral Vision Test), which challenges visual precision by requiring participants to locate bird-shaped symbols appearing for a brief moment in their peripheral field of vision. The test outputs included mean reaction time (brain speed reaction time – BSRT), number of correct responses (brain speed hits – BSH), and number of errors (brain speed errors – BSE). The brain speed quality index (BSQ) was calculated as the ratio of BSRT to BSH, representing processing efficiency. In both cognitive tests, participants responded to 15 visual stimuli presented randomly across the eight semaphores. Reactive agility of the lower limbs was evaluated using the Fitro Agility Check (Horická & Šimonek, 2021; Zemková & Hamar, 2013). This test involved 16 randomly generated visual stimuli—blue circles appearing on a screen in four possible directions (front, rear, left, right). Players responded by stepping on pressure-sensitive mats positioned at the corners of a 40 cm square. All testing procedures followed the official Witty SEM user protocol provided by Microgate (Witty User Manual, 2019). Measurements were performed on the same day and in the same indoor facility to eliminate environmental variation. The number, spatial arrangement, and mounting of sensors were configured exactly according to the manual. Identical calibration and timing protocols were used for all participants. Regarding familiarization, all participants received a standardized verbal explanation and live demonstration of each task. No separate practice trials were performed, as this ensured understanding without introducing learning effects. The cognitive and motor-cognitive tests were performed in a fixed sequence: first the BrainHQ Agility

Test, followed by the BrainHQ Hawk Eye Test, and finally the Fitro Agility Check. Both diagnostic systems have demonstrated high reliability and validity in adolescent populations (Andrašić et al., 2021; Zemková & Hamar, 2013).

Statistics

The mean of the four fastest responses in each direction was used for analysis. A one-way ANOVA (1×4; one factor with four levels) was employed to examine the effect of the grouping factor (training age or field position) on the measured motor-cognitive variables. Because the assumption of normality was violated (Shapiro–Wilk test; non-published results), rank transformation of the raw scores was applied prior to analysis. Homogeneity of variances was verified using Levene’s test. Post hoc multiple comparisons were conducted using the least significant difference (LSD) test, selected due to the presence of statistically significant main effects and the exploratory nature of the study. Although LSD does not ap-

ply correction for multiple comparisons, it allows for greater sensitivity in detecting meaningful group differences. Effect sizes for ANOVA were calculated using eta squared (η^2) and interpreted as follows: <0.010 = no effect; 0.010–0.059 = small; 0.060–0.139 = medium; \geq 0.140 = large. For post hoc pairwise comparisons, Cohen’s d was calculated and interpreted as: 0.20–0.49 = small; 0.50–0.79 = medium; \geq 0.80 = large. Statistical significance was set at $\alpha=0.05$. All analyses were performed using Statistica software, version 13.5 (TIBCO Software Inc., Palo Alto, CA, USA).

Results

Field position did not show statistically significant effects ($p>0.05$), though small-to-moderate tendencies ($\eta^2\approx 0.05$) were observed: midfielders were fastest in BSRT, goalkeepers made the fewest BSE, and defenders had slightly higher BSQ. These patterns suggest positional tendencies rather than true group differences (Table 1).

Table 1. Results of descriptive characteristics of brain speed, disjunctive reactivity, and lower limb reaction speed of soccer players – field position view (presented as mean±SEM [95% CI])

Field post	Goalkeeper (n=12)	Defender (n=57)	Midfielder (n=30)	Striker (n=43)
BSRT (s)	0.442±0.095 [0.234-0.651]	0.555±0.032 [0.490-0.619]	0.554±0.035 [0.483-0.626]	0.516±0.038 [0.439-0.593]
BSE (n)	2.667 ± 0.284 [2.041-3.292]	3.122±0.100 [2.922-3.323]	3.167±0.108 [2.946-3.388]	2.927±0.123 [2.678-3.175]
BSQ (BSRT/BSH)	0.038±0.010 [0.016-0.060]	0.048±0.003 [0.042-0.055]	0.048±0.003 [0.041-0.055]	0.044±0.004 [0.037-0.052]
CDR (s)	23.490±1.228 [20.788-26.192]	27.510±0.885 [25.737-29.281]	26.401±1.263 [23.816-28.986]	29.503±1.641 [26.191-32.815]
Right (ms)	690.05±26.863 [630.92-749.17]	724.13±11.48 [701.12-747.13]	731.27±18.10 [694.18-768.35]	752.81±17.385 [717.7-787.92]
Left (ms)	730.54±39.550 [643.49-817.59]	720.681±11.903 [696.84-744.53]	716.34±19.626 [676.13-756.54]	741.13±16.636 [707.53-774.73]
Front (ms)	710.32±33.389 [636.83-783.81]	740.368±13.146 [714.03-766.70]	727.43±20.055 [686.35-768.51]	762.94±19.787 [722.98-802.91]
Rear (ms)	707.44±32.951 [634.91-779.96]	704.740±11.00 [682.69-726.79]	721.10±18.868 [682.44-759.74]	733.22±14.187 [704.57-761.87]

Note. SEM – standard error of mean; 95% CI – 95% confidence interval; bolded values in agility test directions (Right, Left, Front, Rear) indicate the fastest mean reaction time (i.e., lowest value) per direction across playing positions; BSRT = Brain Speed Reaction Time (s); BSE = Brain Speed Errors (number of incorrect responses); BSH = Brain Speed Hits (number of correct responses); BSQ = Brain Speed Quality (BSRT divided by BSH); CDR = Complex Disjunctive Reaction Time (s); Right, Left, Front, Rear = movement directions in the Fitro Agility Test (ms).

Descriptive and inferential statistics revealed significant training age-related differences in all cognitive-motor and agility variables (Table 2). Training age had a significant effect on all key performance indicators: BSRT ($F(3,138)=3.71$, $p=0.013$, $\eta^2=0.076$), BSE ($F=4.68$, $p=0.004$, $\eta^2=0.094$), BSQ ($F=4.04$, $p=0.009$, $\eta^2=0.082$), and CDR ($F=23.71$, $p<0.001$, $\eta^2=0.34$). Directional agility also demonstrated robust effects across all movement directions ($\eta^2=0.20-0.39$, all $p<0.001$),

confirming substantial developmental gains in reaction speed and coordination. Post hoc tests showed that players with 7–9 years of experience significantly outperformed those with 1–3 years across all agility directions (Cohen’s $d=1.3-1.9$, large effects) and achieved superior cognitive efficiency in BSQ ($d=1.6$). Within-group contrasts revealed slower rear-direction responses in the youngest players ($p<0.05$), suggesting early developmental asymmetries (Table 3; Figure 2).

Table 2. Results of descriptive characteristics of brain speed, disjunctive reactivity, and lower limb reaction speed of soccer players – training age view (presented as mean±SEM [95% CI])

Training age (TA)	TA1-3years (n=25)	TA4-6 years (n=48)	TA7-9 years (n=49)	TA10-13 years (n=20)
BSRT (s)	0.645±0.056 [0.530-0.760]	0.558±0.034 [0.490-0.626]	0.467±0.032 [0.403-0.530]	0.507±0.051 [0.400-0.614]
BSE (n)	3.417±0.146 [3.114-3.720]	3.149±0.101 [2.951-3.347]	2.776±0.110 [2.554-2.997]	2.950±0.170 [2.595-3.305]
BSQ (BSRT/BSH)	0.057±0.006 [0.045-0.069]	0.048±0.003 [0.042-0.055]	0.039±0.003 [0.033-0.046]	0.043±0.005 [0.033-0.054]
CDR (s)	34.333±1.629 [30.972-37.695]	29.943±1.263 [27.402-32.484]	23.727±0.702 [22.316-25.139]	22.615±0.992 [20.539-24.691]
Right (ms)	827.958±21.086 [784.44-871.48]	758.07±10.797 [736.33-779.82]	677.10±10.83 [655.33-698.88]	681.60±16.38 [647.32-715.89]
Left (ms)	813.31±18.574 [774.97-851.64]	752.27±10.687 [730.74-773.79]	685.37±14.932 [655.34-715.39]	661.34±16.83 [626.12-696.55]
Front (ms)	857.13±20.081 [815.68-898.57]	774.31±12.913 [748.30-800.32]	684.79±12.971 [658.71-710.87]	663.15±15.34 [631.03-695.26]
Rear (ms)	789.23±18.926 [750.17-828.29]	735.57±10.817 [713.78-757.35]	677.03±12.508 [651.89-702.19]	681.24±17.16 [645.33-717.16]

Note. SEM – standard error of mean; 95% CI – 95% confidence interval; **bolded values in agility test directions (Right, Left, Front, Rear) indicate the fastest mean reaction time (i.e., lowest value) per direction across training age groups**; BSRT = Brain Speed Reaction Time (s); BSE = Brain Speed Errors (number of incorrect responses); BSH = Brain Speed Hits (number of correct responses); BSQ = Brain Speed Quality (BSRT divided by BSH); CDR = Complex Disjunctive Reaction Time (s); Right, Left, Front, Rear = movement directions in the Fitro Agility Test (ms).

Table 3. Results of one-way ANOVA assessing the effects of playing position and training age on motor-cognitive and agility variables

Test	Factor	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared / η^2
BSRT	Training age	15768.02	3	5256.01	3.71	0.013*	0.076†
	Field post	9834.62	3	3278.21	2.24	0.086	0.047
BSE	Training age	18061.22	3	6020.41	4.68	0.004*	0.094†
	Field post	7397.26	3	2465.75	1.81	0.149	0.038
BSQ	Training age	17076.94	3	5692.31	4.04	0.009*	0.082†
	Field post	9956.48	3	3318.83	2.27	0.083	0.048
CDR	Training age	81147.55	3	27049.18	23.71	0.0001*	0.340‡
	Field post	7424.67	3	2474.89	1.48	0.223	0.031
Right	Training age	86041.49	3	28680.50	24.39	0.0001*	0.348‡
	Field post	5695.98	3	1898.66	1.16	0.328	0.025
Left	Training age	64933.56	3	21644.52	17.48	0.0001*	0.277‡
	Field post	1233.26	3	411.09	0.26	0.864	0.005
Front	Training age	89837.69	3	29945.90	28.54	0.0001*	0.385‡
	Field post	2907.79	3	969.26	0.58	0.627	0.013
Rear	Training age	74597.65	3	24865.88	11.52	0.0001*	0.201‡
	Field post	6451.36	3	2150.45	1.32	0.272	0.028

Note. df – degree of freedom; F – value of ANOVA testing criterion; Sig – p value; p<0.05 are marked with an asterisk (*); † indicates moderate effect size ($\eta^2=0.06-0.13$); ‡ indicates large effect size ($\eta^2\geq 0.14$); BSRT = Brain Speed Reaction Time; BSE = Brain Speed Errors; BSQ = Brain Speed Quality; CDR = Complex Disjunctive Reaction Time; df – degree of freedom; Right/Left/Front/Rear = reaction time in the corresponding direction of the Fitro Agility Test.

Figures 1 and 2 illustrate the principal developmental patterns and effect sizes for practical interpretation.

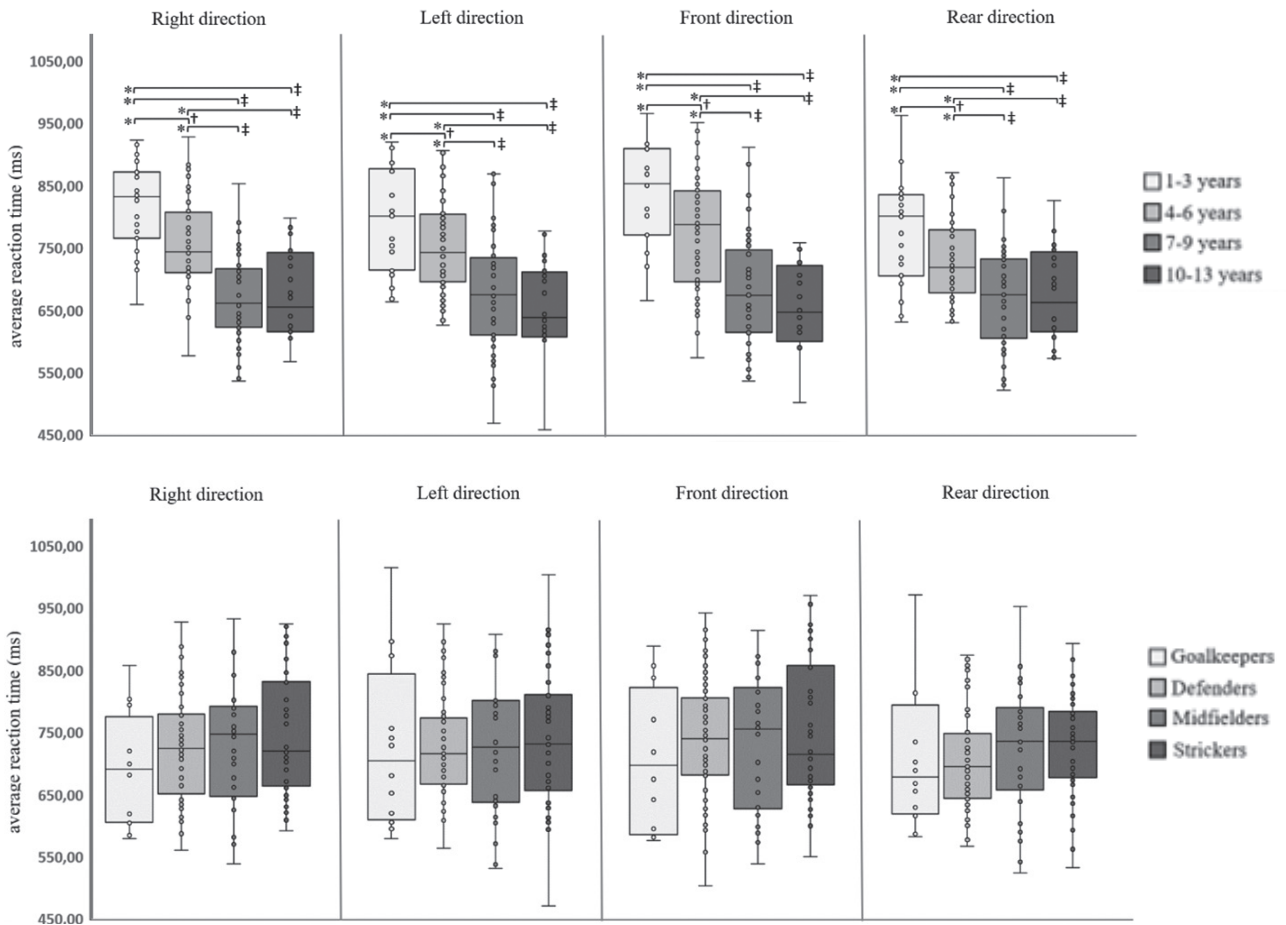


Figure 1. Comparison of reaction time in four movement directions (right, left, front, rear) across training age groups and field positions with identified significant differences based on post hoc analysis

Note. Training age showed large effects across all agility directions, with TA7-9 and TA10-13 groups outperforming TA1-3. Positional trends were small and non-significant. LSD = Least Significant Difference test. Cohen's *d* effect size: † moderate ($0.5 \leq d < 0.8$), ‡ large ($d \geq 0.8$), * = statistically significant differences are indicated at $p < 0.05$.

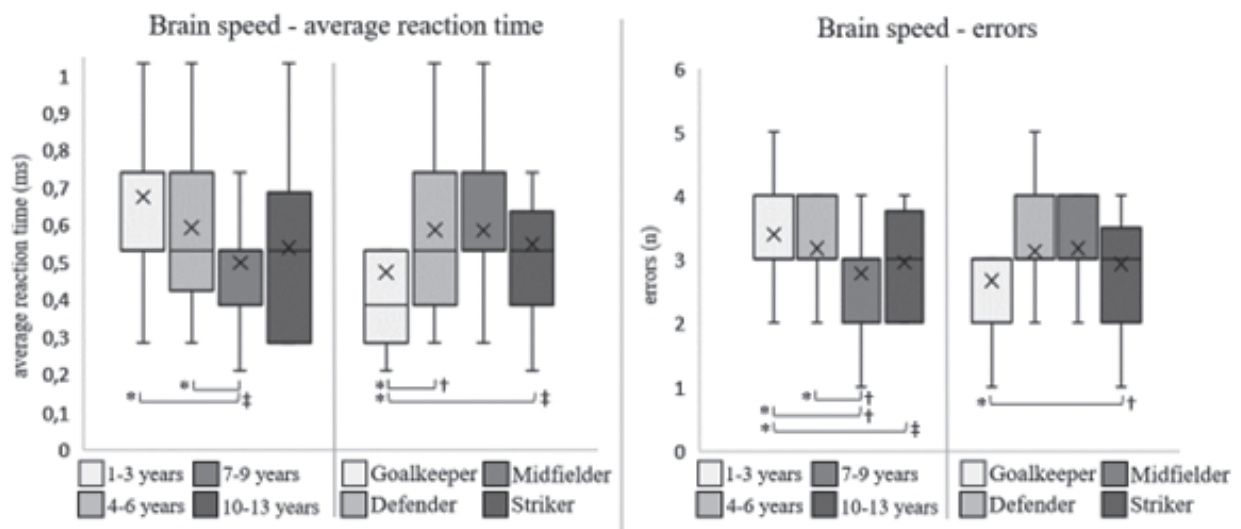
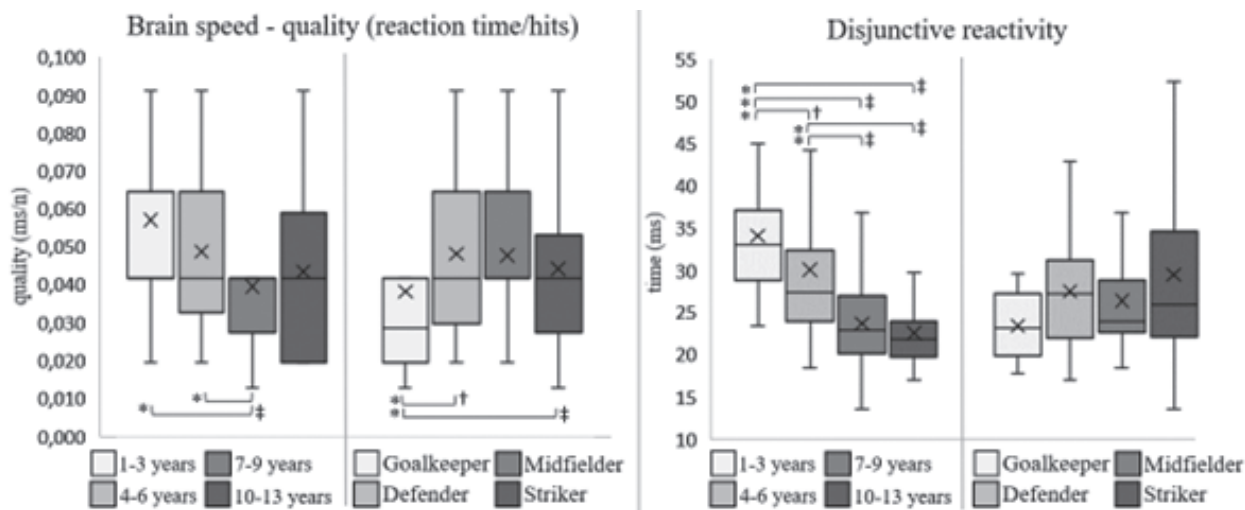


Figure 2. Graphical comparison of performance in brain speed and disjunctive reactivity tasks in relation to training age and field position



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Figure 2. Graphical comparison of performance in brain speed and disjunctive reactivity tasks in relation to training age and field position

Note. Large effects of training age were observed for BSRT, BSQ and CDR. LSD = Least Significant Difference test. Cohen's *d* effect size: † moderate ($0.5 \leq d < 0.8$), ‡ large ($d \geq 0.8$).; * = statistically significant differences are indicated at $p < 0.05$.

Discussion

Development of cognitive-motor abilities by training age

Our findings show a clear developmental progression in cognitive-motor performance associated with training experience. Players with longer sport experience demonstrated faster brain speed reaction times (BSRT), higher brain speed quality (BSQ), and improved directional agility. These results are in line with previous findings highlighting the importance of cumulative sport experience in improving reaction time and agility in youth athletes (Andrašić et al., 2021; Klatt et al., 2021). Moreover, recent evidence confirms that regular football training enhances executive functions such as working memory and inhibitory control (Mao et al., 2024), aligning with our data. Progressive improvements observed across training age groups reflect both neurodevelopmental maturation and the impact of structured cognitive-motor training (Feraco & Meneghetti, 2022). Such gains likely stem from enhanced attentional control and neural efficiency developed through repeated cognitive-motor exposure. The interpretation corresponds with the SMART COMPASS framework, which emphasizes that structured, autonomy-supportive motor learning fosters long-term brain adaptability (Klotzbier & Schott, 2025). Evidence from Meha et al. (2024) further supports this view. Their study showed cognitive benefits, especially in attention and memory, through age-appropriate programs like FUNBALL. Taken together, our results highlight the synergy of biological and experiential factors in adolescent motor-cognitive development (Abarghoueinejad et al., 2021; Bernate et al., 2024).

Positional differences in visual reaction and cognitive efficiency

Playing position did not have statistically significant effects; however, small-to-medium effect sizes indicated minor, non-significant positional tendencies. Midfielders tended to show the fastest BSRT, goalkeepers had the fewest brain speed errors (BSE), and defenders showed the highest BSQ values. These trends partially align with studies identifying higher cognitive load and sustained attention demands in midfield positions (Habekost et al., 2024). Goalkeepers' superior error monitoring may relate to the anticipatory demands of their role (Moreira et al., 2020). Similar positional tendencies have been reported in other studies (Li et al., 2024; Peñalosa et al., 2022), but given the limited sample size of some subgroups, these findings should be interpreted as exploratory rather than conclusive.

Directional agility and disjunctive reaction – age- and position-specific patterns

Our results revealed significant age-related improvements in directional agility, with the TA10–13 group outperforming all others across movement directions. This finding aligns with previous research emphasizing the contribution of neuromotor maturation and accumulated training experience (Thieschäfer & Büsch, 2022). Notably, TA1–3 players responded significantly slower in rear direction, suggesting developmental asymmetries in bilateral coordination. Such directional asymmetries may indicate incomplete neuromotor integration or lateralized attentional control, potentially increasing the risk of movement imbalance or injury if not

addressed through targeted training. These results reinforce the concept of direction-specific motor development (Cartón-Llorente et al., 2024) and highlight the importance of incorporating age-appropriate and multidirectional agility drills (Trecroci et al., 2016). Positional differences in agility were not statistically significant, but descriptive patterns indicated that strikers had faster forward responses and midfielders showed relatively faster rear-direction responses. These tendencies align with the multidimensional agility framework proposed by Dos'Santos and Jones (2022), which links perceptual, biomechanical, and positional factors. Importantly, directional asymmetries identified in younger players may have implications for neuromotor development and injury prevention strategies (Arboix-Alió et al., 2024; Haddad, 2024; Wilkerson et al., 2017).

Visual error processing and brain speed quality (BSQ)

BSQ values improved significantly with training age, suggesting increased visual efficiency and attentional control. Older and more experienced players demonstrated faster processing with fewer errors. These results are consistent with Klatt et al. (2021), who found that experienced youth athletes exhibit lower visual error rates, reflecting more efficient attentional processing. Our data support the use of cognitive-motor assessments (e.g., BSQ) as indicators of training-induced efficiency. Previous work confirms that dual-task and sports-vision interventions enhance attention and decision-making (Ducrocq et al., 2016; Lochhead et al., 2024), supporting BSQ as a practical marker of perceptual-motor integration and cognitive efficiency.

Limitations, application and future directions

This study has several limitations. First, its cross-sectional design limits causal interpretation. Second, uneven subgroup sizes, especially for goalkeepers, restrict generalizability of position-related findings. Third, although Witty SEM and Fitro Agility provide valid measures of motor-cognitive performance, they may not fully capture sport-specific perceptual demands. Finally, despite uniform motivation procedures, individual effort could have introduced variability.

The current findings emphasize the value of integrating perceptual-cognitive diagnostics into youth football training. Players with lower training age demonstrated slower responses, particularly in disjunctive reaction time and rear-direction agility, suggesting the need for targeted interventions to support neuromotor development in these domains. Although positional differences were not statistically significant, the observed tendencies indicate potential cognitive specialization related to field roles, highlighting the importance of individualized, cognitively loaded training. From a practical standpoint, coaches and talent scouts can apply indicators such as BSRT, BSQ, and directional agility to monitor cognitive efficiency and detect developmental lags. Implementing drills targeting rear-direction reactions, visual scanning, and response inhibition may enhance neuromotor control and reduce asymmetry-related injury risk. Diagnostic systems such

as Witty SEM and Fitro Agility provide reliable tools for player profiling, and future longitudinal research should examine their use in monitoring developmental trajectories and neuromotor resilience.

Conclusion

This study demonstrated that brain speed, reaction quality, and lower-limb agility significantly improve with increasing training age in youth soccer players. Large effect sizes in both cognitive (BSRT, BSQ) and motor (CDR, Fitro Agility) indicators suggest substantial neuromotor development between the ages of 7 and 13, with the most pronounced improvements observed in directional agility and brain speed quality. Although positional differences did not reach statistical significance, midfielders showed faster brain reaction times and defenders demonstrated higher brain speed quality, indicating possible neuromotor adaptations based on field roles. These findings emphasize the importance of incorporating cognitive-motor diagnostics into youth soccer training and support the implementation of age-appropriate and directionally targeted drills to enhance reactive performance.

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Conflict of interest

The authors declare that there is no conflict of interest with any financial organization in relation to the research problem discussed in the manuscript.

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Ethical approval information

Measurements were taken according to the ethical standards of the Declaration of Helsinki. The research was approved by Ethical Commission of University of Prešov (ECUP032023PO). Participation in the study was fully voluntary and anonymous. A participant's legal guardian received a written description of the study procedures before testing and submitted a written informed consent to participate in this study.

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Context is Key: University Sports Practice and its Influence on Sleep Patterns

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Abstract

Sleep is an essential component of health and is subject to deprivation in university and sports contexts. Its relationship with physical activity can be beneficial or harmful, depending on intensity and volume. This study investigated the influence of sports practice on the sleep patterns of university students, comparing athletes and non-athletes. Sixty UFPE students took part, 30 athletes (15 men and 15 women) and 30 non-athletes (15 men and 15 women), who answered the International Physical Activity Questionnaire (IPAQ), the Pittsburgh Sleep Quality Index (PSQI) and the Epworth Sleepiness Scale (ESS). Statistical analyses were carried out using parametric and non-parametric tests ($p < 0.05$). Athletes had longer total sleep time (6.88 ± 1.32 h vs. 6.03 ± 1.07 h; $p = 0.01$; $ES = 0.70$) and better overall sleep quality (6.87 ± 3.05 vs. 8.40 ± 3.06 ; $p = 0.04$; $ES = 0.78$) compared to non-athletes. Analysis by gender indicated that male athletes had longer sleep times (6.90 ± 1.34 h vs. 6.00 ± 1.13 h; $p = 0.05$; $ES = 0.72$), better subjective (0.46 ± 0.69 vs. 1.07 ± 0.70 ; $p = 0.02$; $ES = 0.89$) and global sleep quality (5.87 ± 3.50 vs. 8.13 ± 3.04 ; $p = 0.04$; $ES = 0.69$) than male non-athletes, while among women there was a trend towards better patterns in the athlete group, with no significant differences. No differences were found in daytime sleepiness between the groups. The study concludes that regular sports practice is associated with healthier sleep patterns, especially among men, reinforcing the importance of institutional actions that encourage sport in the university environment as a health promotion strategy.

Keywords: *university students, sport, physical activity, sleep quality*

Introduction

Sleep is an essential physiological process for maintaining health and the proper functioning of bodily and mental functions (Irwin & Opp, 2017). Characterized by a reduction in consciousness and neuromuscular activity, sleep plays a fundamental role in memory consolidation, hormonal modulation and general body repair (Logan & McClung, 2019). Poor sleep quality and associated disorders can increase the risk of obesity, cardiovascular disease, impaired learning and cognition, as well as compromising mental health and quality of life and promoting physical inactivity (Fattinger et al., 2017; Ghrouz et al., 2019; Velasquez-Melendez et al., 2021; Wang & Bíró, 2021).

Physical activity, in turn, can significantly influence sleep, affecting aspects such as subjective perception, efficiency, latency, duration and quality, according to the frequency, intensity and type of exercise performed (Oliveira et al., 2018). Santiago et al. (2022) showed that adolescents involved in regular sports and exercise programs had better quality and longer duration of sleep compared to those who did not practice physical activities. Physical activity is defined as any bodily movement that results in an energy expenditure greater than the resting state (De Araujo Vasconcelos et al., 2024).

However, the relationship between sleep and physical activity is bidirectional. Depending on the intensity and duration of the exercise or modality practiced, different repercussions can be observed on sleep patterns (Ghrouz et al., 2019). While

moderate physical activity tends to promote improvements in sleep quality, high levels of effort, such as those observed in athletes, can be associated with sleep disorders, including insomnia and excessive daytime sleepiness (Memon et al., 2021; Santiago et al., 2022).

In the university context, students face a series of challenges, such as academic demands, family pressures and socioeconomic difficulties, factors that can compromise sleep quality. Such conditions increase daytime sleepiness, reduce adherence to physical activity and contribute to a more sedentary lifestyle (Almutairi et al., 2018). Evidence indicates that many university students do not meet the minimum recommendations for sleep and physical activity, which negatively impacts their general health and academic performance (Martins et al., 2020; Nikolic et al., 2023).

In the case of university athletes, this relationship requires an even more specific analysis. In addition to academic demands, these individuals face intense training and competition routines, which can result in sleep deprivation and deterioration in sleep quality (Leduc et al., 2020). These factors are directly associated with deficits in physical and cognitive performance, as well as increasing the risk of injury (Irwin & Opp, 2017; Leduc et al., 2020).

Excessive daytime sleepiness is an important indicator of sleep-related disorders, characterized by difficulty staying awake during the day and the occurrence of unintentional naps (Schlarb et al., 2017). Regular physical activity has been shown to improve sleep quality and reduce levels of daytime sleepiness in students and young athletes (Ghrouz et al., 2019; Oliveira et al., 2018; Rosi et al., 2020).

Despite recent scientific interest in the relationship between physical activity and sleep patterns among university students, there is still a gap in studies that analyze these variables in an integrated and comparative manner in student athletes and non-athletes within institutions. Investigations with this focus are essential to better understand this association and to guide interventions aimed at improving sleep quality, especially in populations exposed to high levels of physical and mental stress (Almutairi et al., 2018).

In view of the above, the aim of this study was to investigate the influence of sports practice on sleep patterns among athletes and university students. The hypothesis is that involvement in sports is associated with higher levels of physical activity and better sleep patterns. The results could support health promotion strategies aimed at both the general university public and athletes, helping to formulate institutional policies that encourage regular physical activity and promote a balance between academic and sporting demands and adequate rest.

Materials and methods

Participants and design

This is an observational, cross-sectional, descriptive study with a quantitative approach (Thomas, Nelson, & Silverman, 2012). The project was approved by the Research Ethics Committee (CEP) of the Health Sciences Center of the Federal University of Pernambuco (CCS-UFPE), under opinion no.

3.492.898, and followed the guidelines established by Resolution 466/12 of the National Health Council. All participants signed the Free and Informed Consent Form (FICF) and voluntarily agreed to take part in the study, and could withdraw at any time.

For inclusion, volunteers had to be aged 18 or over, enrolled in an undergraduate course at UFPE and be part of a university sports team or not. University athletes were those who had been part of a sports team for at least three months. Individuals who did not fill in the questionnaires completely, missed any stage of the investigation or were taking sleep-inducing or sleep-regulating medication were excluded. Participants were recruited by advertising on social media, as well as by distributing pamphlets placed in strategic locations in UFPE and given to the coaches of university sports teams. The pamphlets contained instructions on how to contact those responsible for the research, via telephone or in person.

The total number of participants was defined by sample calculation using the G*Power software (Faul et al., 2007), considering an effect size of 0.8, a statistical power of 90% and a significance level of 5%. This estimated a number of 56 participants, 28 in each group, to be able to identify significant differences. Initially, 88 students expressed an interest in taking part, 40 of whom were university athletes. After applying the inclusion and exclusion criteria, 28 students were disregarded, 10 athletes and 18 non-athletes. The final sample comprised 60 students, divided into two groups: a group of university athletes (GAU), with 30 participants, and a group of non-athletes (GNA), also with 30 participants.

Procedures

Both groups (GAU and GNA) underwent three visits, each on different and previously scheduled days, as illustrated in Figure 1. On the first visit, participants went to the research group's laboratory for anthropometric measurements. On the second visit, the International Physical Activity Questionnaire (IPAQ) and the Epworth Sleepiness Scale (ESS) were administered. And on the third visit, the Pittsburgh Sleep Quality Index (PSQI) was administered. The researchers were present to answer any questions regarding the questionnaires. This division was due to the size of the instruments, since the PSQI is more extensive compared to the IPAQ and ESS. The aim was to have as little impact as possible on the daily routine of students and university athletes.

In order to avoid potential interference in the variables of interest, in the GNA group, data collection took place during periods without exams or academic work. In the GAU group, a specific sport was chosen in order to standardize the demands and inherent characteristics. The duration and intensity of training on the days scheduled for data collection were standardized with the respective coaches in advance. The procedures were explained, and the date and time for data collection were set by mutual agreement, taking into account the training schedule of the men's and women's volleyball teams. Data collection took place during periods of the season without games or competitions, which could generate high levels of stress and anxiety, potentially compromising the analysis of this investigation.

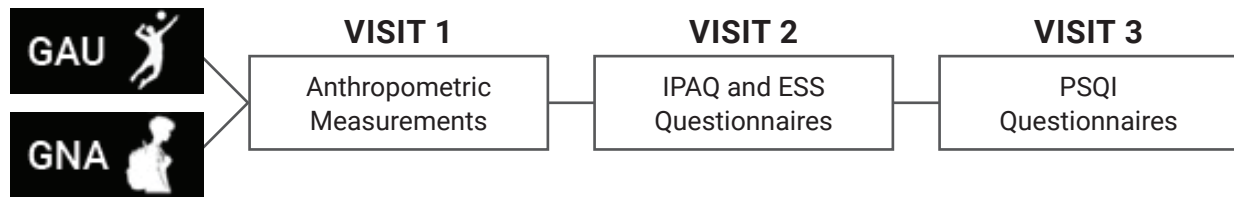


Figure 1. Procedures

Note: The visits were conducted on separate, pre-scheduled days.

Instruments

Body mass was measured using a portable scale (model PL 200, Filizola S.A., São Paulo, Brazil), and height was assessed using a portable stadiometer (Sanny, São Paulo, Brazil). With these two values, the Body Mass Index (BMI) was calculated, obtained by dividing the body mass (kg) by the height squared (m^2) of each participant (Peterson et al., 2016).

To assess the volunteers' PAL, we used the IPAQ, short version, validated and adapted for the Brazilian population by Matsudo et al. (2001). It is a self-administered instrument made up of seven questions referring to the previous week. The IPAQ estimates the duration (minutes per day), intensity (in metabolic equivalents of tasks - METs) and frequency (days per week) of the physical activities performed, making it possible to classify the participants into the categories "very active", "active", "irregularly active" (A and B) and "sedentary".

Sleep quality was measured using the PSQI, adapted and validated for the Brazilian population by Bertolazi et al. (2011). This questionnaire covers the last 30 days and assesses seven domains: sleep duration, sleep efficiency, sleep latency, subjective sleep quality, sleep disturbances, daytime dysfunctions and use of sleep medication. Each item is scored from 0 to 3, and the total score is obtained by adding up the scores of the seven domains, ranging from 0 to 21 points. Values between 0 and 4 indicate good sleep quality; between 5 and 10, poor sleep quality; and scores above 10 suggest the presence of sleep disorders.

Daytime sleepiness was assessed using the ESS, adapted and validated for Brazil by Bertolazi et al. (2009). This instrument contains eight questions describing everyday situations likely to cause sleepiness (napping). The ESS classifies sleepiness into normal, moderate and excessive levels. The total score ranges from 0 to 24 and is interpreted as follows: 1 to 6 indicates normal sleepiness; 7 to 8, moderate sleepiness; and 9 to 24, excessive or abnormal sleepiness (Johns, 1991).

Statistics

Initially, the sample was characterized using descriptive statistics, using means and standard deviations. The data was then submitted to the Shapiro-Wilk normality test. Variables with a normal distribution were analyzed using Student's t-test for independent samples, while those with a non-normal distribution were analyzed using the Mann-Whitney test. In addition, the effect size for the comparisons was calculated using Cohen's d, with the following interpretation parameters: very small effect (between 0.0 and 0.19), small effect (between 0.20 and 0.49), medium effect (between 0.50 and 0.79) and large effect (equal to or greater than 0.80).

The analyses included inter-group comparisons (between GAU and GNA, in total and stratified by sex) and intra-group comparisons (male vs. female within GAU and GNA, male GAU vs. male GNA, female GAU vs. female GNA), considering NAF, sleepiness and sleep parameters. The correlation between NAF, sleepiness and sleep parameters was assessed using Pearson's correlation test for variables with a normal distribution and Spearman's correlation test for variables with a non-normal distribution. All statistical analyses were carried out using IBM SPSS Statistics for Windows software, version 20.0 (Armonk, NY: IBM Corp). The significance level adopted was 5% ($p < 0.05$).

Results

The sample consisted of 60 participants, 30 university athletes (GAU; 15 men and 15 women) and 30 non-athlete university students (GNA; 15 men and 15 women). The participants had an average age of 21.80 ± 2.58 years, an average height of 170 ± 24.20 cm, an average body mass of 72.90 ± 12.70 kg and an average Body Mass Index (BMI) of 24.50 ± 3.36 kg/ m^2 , with no significant difference in these variables between the GAU and GNA groups ($p > 0.05$). The groups were homogeneous. The complete characterization of the sample is shown in Table 1.

Table 1. General characteristics of the sample

	Total (n=60) Mean \pm SD	GAU (n=30) Mean \pm SD	GNA (n=30) Mean \pm SD	P
Age (years)	21.80 \pm 2.58	22.40 \pm 2.72	21.10 \pm 2.30	0.05
Height (cm)	170.00 \pm 24.20	175.00 \pm 10.50	165.00 \pm 32.00	0.09
Body mass (kg)	72.90 \pm 12.70	75.30 \pm 11.00	70.60 \pm 14.00	0.15
BMI (kg/ m^2)	24.50 \pm 3.36	24.60 \pm 3.08	24.50 \pm 3.67	0.88

GAU: Group of university athletes; GNA: Group of non-athletes; BMI: Body Mass Index

In the following tables, Cohen's effect size was used with the following interpretation parameters: very small (between 0.0 and 0.19), small (between 0.20 and 0.49), medium (between 0.50 and 0.79), and large (equal to or greater than 0.80). Table 2 shows that there was a difference in total sleep time (p=0.01; ES=0.70), with GAU reporting approximately

12.35% more sleep time. In addition, there was a significant difference in overall sleep quality (p=0.04; ES=0.78), with GAU reporting 22.27% better sleep quality than GNA. The lower the PSQI score, the better the sleep quality (Bertolazi et al., 2011).

Table 2. Inter-group comparison between GAU and GNA in terms of level of physical activity, sleepiness and sleep patterns

Variable	Group	Mean ± SD	Δ (Δ %)	p	(ES)
IPAQ (score)	GAU	1.84±0.83	0.19	0.37	0.23
	GNA	2.03±0.89	(10.33)		
Sleepiness (score)	GAU	1.30±0.87	0.03	0.88	0.03
	GNA	1.33±0.84	(2.31)		
Total sleep time (h)	GAU	6.88±1.32	0.85	0.01	0.70*
	GNA	6.03±1.07	(12.35)		
Sleep latency (min)	GAU	39.10±37.90	13.1	0.11	0.41
	GNA	26.00±23.90	(33.50)		
Sleep efficiency (%)	GAU	88.70±12.10	4.00	0.14	0.38
	GNA	84.70±8.34	(4.51)		
Subjective sleep quality (score)	GAU	0.80±0.66	0.33	0.06	0.49
	GNA	1.13±0.68	(41.50)		
Overall sleep quality (score)	GAU	6.87±3.05	1.53	0.04	0.78*
	GNA	8.40±3.06	(22.27)		

GAU: Group of university athletes; GNA: Group of non-athletes; p<0.05; * Mean effect

In table 3, among the men, there was a significant difference on total sleep time (p=0.05; ES=0.72), with GAU having 13.04% more total time. Similarly, statistically significant differences were found in subjective sleep quality (p=0.02; ES=0.89) and global sleep quality (p=0.04; ES=0.69), with GAU showing a 6.19% better subjective quality and a 38.50% better global quality than GNA, respectively. In addition, sleep latency was 47.95% greater in the GAU (ES=0.65).

Among the women, there were no statistically significant differences between the groups; however, there was a trend towards better sleep patterns in the GAU, especially in relation to total time and sleep efficiency. Women in the GAU had 11.64% longer total sleep time (ES=0.66) and 5.70% higher sleep efficiency (ES=0.46) compared to those in the GNA. On the other hand, the level of physical activity was 33.13% higher in GNA compared to GAU (ES=0.61).

Table 3. Inter-group comparison between participants of the same sex from the UAG and the NAG in terms of physical activity level, sleepiness and sleep patterns

Variable	GAU Mean ± SD	GNA Mean ± SD	Groups	Δ(Δ%)	p	ES
IPAQ (score)	2.07±0.79	1.93±0.88	Mal vs Mal	6.76 (1.93)	0.66	0.15
	1.60±0.82	2.13±0.91	Fem vs Fem	0.53 (33.13)	0.10	0.61*
Sleepiness (score)	1.20±0.86	1.33±0.81	Mal vs Mal	0.13 (10.83)	0.66	0.15
	1.40±0.91	1.33±0.90	Fem vs Fem	0.07 (5.00)	0.84	0.07
Total sleep time (h)	6.90±1.34	6.00±1.13	Mal vs Mal	0.90 (13.04)	0.05	0.72*
	6.87±1.36	6.07±1.03	Fem vs Fem	0.80 (11.64)	0.08	0.66*

(continued from previous page)

Table 3. Inter-group comparison between participants of the same sex from the UAG and the NAG in terms of physical activity level, sleepiness and sleep patterns

Variable	GAU Mean \pm SD	GNA Mean \pm SD	Groups	$\Delta(\Delta\%)$	p	ES
Sleep latency (min)	51.30 \pm 49.70	26.70 \pm 18.87	Mal vs Mal	24.60(47.95)	0.08	0.65*
	27.00 \pm 13.70	25.30 \pm 28.69	Fem vs Fem	1.70 (6.30)	0.84	0.07
Sleep efficiency (%)	89.80 \pm 11.20	86.80 \pm 9.25	Mal vs Mal	3.00 (3.34)	0.43	0.29
	87.70 \pm 13.20	82.70 \pm 7.03	Fem vs Fem	5.00 (5.70)	0.21	0.46
Subjective sleep quality (score)	0.46 \pm 0.64	1.07 \pm 0.70	Mal vs Mal	0.61(132.61)	0.02	0.89**
	1.13 \pm 0.51	1.20 \pm 0.67	Fem vs Fem	0.07 (6.19)	0.76	0.11
Overall sleep quality (score)	5.87 \pm 3.50	8.13 \pm 3.04	Mal vs Mal	2.26 (38.50)	0.04	0.69*
	7.87 \pm 2.20	8.67 \pm 3.15	Fem vs Fem	0.80 (10.17)	0.42	0.29

GAU: Group of university athletes; GNA: Group of non-athletes; $p < 0.05$; Mal: Male; Fem: Female; * Medium effect; ** Large effect

Table 4 shows that in the GAU, it was observed that men had better sleep quality, with a 145.65% lower subjective quality ($p=0.01$; $ES=1.15$), and a 34.07% lower overall quality ($p=0.01$; $ES=0.68$). In addition, a medium effect size was observed in the level of physical activity, with men being superior (22.71%; $ES=0.54$), the same occurring with sleep latency, which showed a medium effect ($ES=0.66$), being 47.37% higher in men.

In the GNA, no statistically significant differences were found between men and women. However, there was an average effect ($ES=0.50$) on sleep efficiency, with men showing 4.72% greater efficiency than women. Regarding the correlations between the level of physical activity and sleep and sleepiness patterns, no significant associations were observed in the total group ($n=60$).

Table 4. Intra-group comparison between male and female UAG and NAG participants in terms of physical activity level, sleepiness and sleep patterns

Variable	Male Mean \pm SD	Female Mean \pm SD	$\Delta(\Delta\%)$	p	ES
GAU					
IPAQ (score)	2.07 \pm 0.79	1.60 \pm 0.82	0.47 (22.71)	0.12	0.54*
Sleepiness (score)	1.20 \pm 0.86	1.40 \pm 0.91	0.20 (16.67)	0.54	0.22
Total sleep time (h)	6.90 \pm 1.34	6.87 \pm 1.36	0.03 (0.43)	0.94	0.02
Sleep latency (min)	51.30 \pm 49.70	27.00 \pm 13.70	24.30(47.37)	0.07	0.66
Sleep efficiency (%)	89.80 \pm 11.20	87.70 \pm 13.20	2.10 (2.34)	0.63	0.17
Subjective sleep quality (score)	0.46 \pm 0.64	1.13 \pm 0.51	0.67 (145.65)	0.01	1.15**
Overall sleep quality (score)	5.87 \pm 3.50	7.87 \pm 2.20	2.00 (34.07)	0.01	0.68*
GNA					
IPAQ (score)	1.93 \pm 0.88	2.13 \pm 0.91	0.20 (10.36)	0.54	0.22
Sleepiness (score)	1.33 \pm 0.81	1.33 \pm 0.90	0.00 (0.00)	1.00	0.00
Total sleep time (h)	6.00 \pm 1.13	6.07 \pm 1.03	0.07 (1.17)	0.86	0.06
Sleep latency (min)	26.70 \pm 18.87	25.30 \pm 28.69	1.40 (5.24)	0.88	0.05
Sleep efficiency (%)	86.80 \pm 9.25	82.70 \pm 7.03	4.10 (4.72)	0.17	0.50*
Subjective sleep quality (score)	1.07 \pm 0.70	1.20 \pm 0.67	0.13 (12.15)	0.60	0.19
Overall sleep quality (score)	8.13 \pm 3.04	8.67 \pm 3.15	0.54 (6.64)	0.64	0.17

GAU: Group of university athletes; GNA: Group of non-athletes; $p < 0.05$; * Medium effect; ** Large effect

Discussion

This study aimed to investigate the influence of sports practice on sleep patterns among university athletes and university students. In academic environments, it is common for undergraduate students to face irregular routines, high cognitive demands and psychosocial stressors, which can compromise sleep duration and quality, as well as increasing daytime sleepiness (Wang & Bíró, 2021). Despite the recognized association between physical activity and improved sleep parameters, few observational studies directly compare student athletes and non-athletes in the university context.

The results of this investigation indicate that there were significant differences in total sleep time, with GAU reporting approximately 12.35% more sleep time. There was also a difference in overall sleep quality, with UAG having a 22.27% higher sleep quality than NAG. This reinforces the hypothesis that the routine and lifestyle linked to sport can act as a protective factor for sleep health in a population known to face routines that compromise sleep (Wang & Bíró, 2021). Furthermore, these findings draw attention to the fact that this improvement in the quality and duration of athletes' sleep was evident during periods outside of competitions and games. It is important to note that competitive moments throughout a season must be monitored and given special attention by the professionals responsible for ensuring adequate recovery, quality sleep, and sufficient sleep duration. In contrast, Leduc et al. (2020) directly compared athletes and non-athletes from a Canadian university during periods of intense training and competition. These authors observed shorter average sleep duration in athletes and no significant difference in the overall PSQI score. The discrepancy with our findings is possibly related to the fact that data collection in our study took place outside of competitive phases, when the training load is more stable and provides more rest time for athletes, while in the Canadian study the competitive load may have reduced TTS and masked any differences in subjective quality.

When comparing the groups of the same sex, some significant differences were observed among the men. GAU males had a higher total sleep time ($p=0.05$; $ES=0.72$), subjective sleep quality ($p=0.02$; $ES=0.89$) and global sleep quality ($p=0.04$; $ES=0.69$) than GNA. Among the women, there were no statistically significant differences between the groups; however, there was a trend towards better sleep patterns in the UAG, especially in relation to total time and sleep efficiency. GAU females had 11.64% longer total sleep time ($ES=0.66$) and 5.70% higher efficiency ($ES=0.46$) compared to GNA females. Dolezal et al. (2018) and Gubelmann et al. (2018) agree with these findings when they indicate that individuals with greater objective physical activity have greater sleep efficiency and are associated with better subjective sleep quality, reinforcing that the correlations observed in university students who practice sports reflect trends in the general population.

A particular finding in this study, although not significant, was the result for females, in which those in the GNA had a 33.13% higher level of physical activity than those in the GAU. This raises a few hypotheses: firstly, it's possible that the athletes display a "compensatory sedentary lifestyle". Suggesting that the high volume and intensity of training generates

fatigue that needs to be managed, leading to a reduction in non-exercise-related physical activity (e.g. active leisure, domestic activities, commuting) as part of a recovery strategy to balance the total stress load to which athletes are subjected (Hayes-Ortiz et al., 2023). Secondly, the student-athlete's routine can impose an overload of roles that can limit the practice of physical activities beyond structured training, such as the use of active transportation on campus and other unstructured leisure activities in everyday life. The need to reconcile the demands of sport with academic and personal life is a central aspect of athletic career development (Carballo-Fazanes et al., 2020).

As for the sexes in each group, it was observed that men in the UAG had better sleep quality, both subjective ($p=0.01$; $ES=1.15$) and global ($p=0.01$; $ES=0.68$). In addition, higher levels of physical activity were found in men (22.71%; $ES=0.54$). This finding, which was absent in the GNA, suggests that factors inherent in the routine of university sport may exacerbate the differences in sleep expected between the sexes. A possible explanation for this disparity may lie in the distinct psychophysiological response to the stress of the double shift found in females. Women tend to have greater reactivity of the hypothalamic-pituitary-adrenal (HPA) axis, which is reflected in an increase in plasma cortisol with a low resolution rate (Graves et al., 2021; Irwin & Opp, 2017). This is associated with increased sleep latency and fragmentation and a reduction in deep sleep, due to the antagonistic feedback between cortisol and melatonin (Logan & McClung, 2019). Recent studies corroborate this line of thought, indicating that female university athletes do, in fact, report significantly higher levels of perceived stress than their male counterparts (Graves et al., 2021), and stress is one of the main factors negatively affecting sleep quality. Additionally, another line to consider involves the hormonal differences of the female menstrual cycle, which influence sleep architecture and recovery, and may have their impact amplified by the high training load (Baker & Lee, 2018). This physiological peculiarity could explain less efficient sleep recovery, combined with a greater perception of effort and stress.

The absence of significant differences between men and women in GNA reinforces the assumption that the competitive environment and the high demands of training are the likely catalysts for these differences, suggesting that university athletes may constitute a subgroup that requires special attention with regard to sleep health. This finding is consistent with Wang and Bíró (2021), who identified in a systematic review that, in university students, behavioral and contextual factors such as chronotype, academic stress or the use of electronics have a greater influence on sleep quality than biological sex alone.

Furthermore, a paradoxical observation from the present study concerns the domains of sleep latency and efficiency. Specifically, the men from the UAG showed a tendency towards longer sleep latency compared to those from the NAG, with a difference of almost 25 minutes ($p=0.08$; $ES=0.65$), and also in relation to their female colleagues ($p=0.07$; $ES=0.66$). On the other hand, these same male athletes also exhibited a tendency, albeit with a smaller effect, towards greater sleep efficiency compared to non-athletes ($p=0.43$; $ES=0.29$). This

shows that even though male university athletes took longer to start sleeping, they were able to sleep better and more restoratively. This pattern suggests that, in males, the training load may induce a strong psychophysiological arousal response at the end of the day, which makes it difficult to start sleeping. This hypothesis is plausible, since the literature indicates that intense exercise can increase sympathetic nervous system activity, impacting falling asleep (Santiago et al., 2022). This psychophysiological arousal causes simultaneous activation of central and peripheral systems linked to the regulation of wakefulness and alertness, such as the HPA axis, which can increase latency and reduce sleep time (Logan & McClung, 2019). It also causes a decrease in parasympathetic nervous system activity accompanied by an increase in sympathetic nervous system activity, leading to higher heart rate and body temperature due to the release of catecholamines, e.g., adrenaline (Dolezal et al., 2017; Fattinger et al., 2017).

At the same time, the biological need for more restful sleep for physical recovery, reflected in a tendency towards greater efficiency, is also present, consistent with the increased homeostatic pressure for slow-wave sleep after exercise (Memon et al., 2021). Female athletes exhibited a similar pattern, with GAU taking longer to fall asleep and demonstrating greater sleep efficiency, but with lower latency ($ES=0.07$) and higher efficiency ($ES=0.46$). The absence of the “cost” of latency, combined with the “benefit” of efficiency, raises the hypothesis that the female athletes in the present study may have a distinct neurophysiological response to training. It is possible that women are less susceptible to exercise-induced arousal of the sympathetic nervous system, or that hormonal factors may modulate this response, protecting sleep onset (Baker & Lee, 2018). Thus, while male athletes’ sleep reflects a balance between the two competing physiological effects, female athletes appear to obtain the restorative sleep benefits associated with exercise without the same penalty in sleep onset.

There were no significant differences between GAU and GNA, and between the sexes in daytime sleepiness, with the groups showing similar values. Kline (2014) found that moderate levels of physical activity are not always associated with changes in daytime sleepiness scores, especially in individuals without clinical insomnia. This is in line with Leduc et al. (2020) who also found no differences in daytime sleepiness between athletes and non-athletes, although they reported a subjective improvement in sleep quality only indirectly.

In summary, this study showed that there was no significant relationship between levels of physical activity and sleep patterns in university students. It was found that the group of belonging, athlete or student, and gender have a more relevant impact on specific aspects of sleep, in terms of duration and quality, reinforcing the hypothesis that the routine and lifestyle associated with regular sports practice can positively influence sleep parameters, especially at times when there is no competitive overload. This finding opens the way for future research to explore whether these differences are maintained in contexts of greater training load or in different age groups.

This study has some limitations to be considered: the cross-sectional design prevents causal inferences between sports practice and sleep indicators; the sample was restricted to students from a single public university and was collect-

ed outside of competitive periods, which may have favored the GAU by registering a lower training overload. The use of self-reported instruments (PSQI, ESS, IPAQ) brings the potential for memory and perception biases, although these instruments are validated and have been applied under supervision to minimize misunderstandings. The lack of objective measures of sleep, such as actigraphy, and physical activity, such as quantification in metabolic equivalent of task (MET), which somewhat limits the accuracy of estimates. And some uncontrolled variables that could interfere with the relationship addressed, such as university shift routine, study hours, and internships.

Considering the scarcity of specific experimental and cross-sectional studies in university students and the variability of findings, it is recommended that future research adopt longitudinal and multicenter designs, use objective sleep measures and control for contextual variables such as training load, academic load and the use of electronic devices. This could confirm the direction and magnitude of the associations and effects between sports practice and sleep parameters in different university settings.

The findings of this study reinforce the importance of promoting structured physical activity in the university environment as a non-pharmacological strategy to improve students’ sleep. As well as the proper balance between academic and sports demands and adequate rest. Providing subsidies for the formulation of institutional policies aimed at encouraging the practice of sports. Furthermore, it helps physical education health professionals, such as coaches, to take an integrated approach in the pursuit of better health and performance, especially in these contexts of high cognitive demand and academic stress, in which this population is inserted.

Conclusions

Regular sports practice among university students is associated with better sleep patterns in terms of duration and subjective quality, especially among males. The findings reinforce the importance of institutional strategies that encourage and provide greater engagement in sports within universities as an effective means of promoting health in the academic context. Future studies should use objective measures to assess physical activity levels and sleep quality in order to strengthen this body of evidence.

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Conflict of interest

The authors declare no conflicts of interest.

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Relationships of Selected Parameters of Isokinetic Strength and Explosive Power in Mixed Martial Arts Fighters

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Abstract

In mixed martial arts (MMA), muscle strength manifests in multiple directions, movement velocities and all types of muscle contractions, with explosive and maximal strength considered the most relevant for performance. The aim of the study was to elucidate the relationships between isokinetic strength and explosive power in MMA fighters. The study involved 17 male MMA fighters competing at national level (18.00 ± 1.00 years), with a competitive record of 2.00 ± 1.50 fights. The following tests were administered to determine explosive power by Optogait: standard countermovement push-up, kneeling countermovement push-up, and kneeling stop push-up for upper limbs, and countermovement jump, countermovement jump with free arms, and squat jump for lower limbs. Time to peak torque (TTPT) and peak torque (PT) as indicators of isokinetic strength were measured by HUMAC NORM with a focus on the extensors and flexors of the knee, hip, shoulder, and elbow joints during concentric, eccentric, and isometric muscle contractions. The results showed significant correlations ($p < 0.05$; $r > 0.5$) between explosive power of lower limbs and PT of knee and hip extensors during selected contractions. In upper limbs, results showed significant correlation ($p < 0.05$; $r > 0.5$) between performance in standard countermovement push-up and PT of elbow and shoulder flexors during selected contractions. The results showed that TTPT did not significantly affect the level of explosive power ($p > 0.05$), except in the case of elbow flexors during concentric contraction ($p = 0.024$; $r = -0.543$). The level of isokinetic strength of lower limbs affects the level of explosive power in complex movement, which may be beneficial for executing specific movements in fights.

Keywords: muscle strength, time to peak torque, peak torque, isokinetic dynamometry, combat sports, MMA

Introduction

Mixed martial arts (MMA) incorporates techniques from various combat sports. Because of its complexity, athletes must not only master a wide range of techniques but also achieve a high level of strength, condition and all-around physical readiness (Amtmann, 2004).

After considering the specificities of MMA, Lenetsky and Harris (2012) identify four determining motor abilities: explosive strength, absolute strength, endurance, and flexibility. The most successful fighters possess elite fighting skills and extraordinary strength and conditioning levels (Kostikiadis et al., 2018; Tota, Pilch, Piotrowska, & Maciejczyk, 2019)

Due to the nature and variety of MMA, muscle strength is exerted in various directions, at different speeds, and in all muscle modes (Folhes, Reis, Marques, Neiva, & Marques, 2022). Therefore, MMA demands high absolute strength in both upper and lower limbs in concentric, eccentric, and isometric modes (Bagley et al. 2015; Plush, Stuart, Nosaka, & Barley, 2022). Andrade, Flores, Andreato and Coimbra (2019) agree that high levels of dynamic and isometric strength in upper and lower limbs of MMA athletes increase the level of skills used in matches.

According to Spanias, Nikolaidis, Rosemann and Knechtle (2019), upper and lower limb strength plays a key

role in grappling. Both isometric and dynamic strength are important in grappling. According to Vecchio, Hirata and Franchini (2011), approximately 50% of MMA matches end during ground fighting, so it is important to develop these skills. Maximal strength also positively impacts performance, endurance, and injury prevention (James, Haff, Kelly, & Beckman, 2016).

Another important fact is that punch force comes from the lower limbs. Force generated by the legs is further transmitted to the trunk and the upper limbs. This factor is a key determinant that differentiates the stand-up fighting of MMA fighters at a higher performance level from those with a lower level of technical and physical readiness (Spanias, Nikolaidis, Rosemann, & Knechtel, 2019).

The expression of power is also crucial for MMA fighters, especially when performing punches and kicks, where immediate application of force in unloaded conditions is essential. Aagaard, Simonsen, Andersen, Magnusson and Dyhre-Poulsen (2002) noted that a punch is delivered in approximately 50–250 ms. Thus, the rate of force development, which determines the ability to produce a high level of force in a short time, is decisive for the effectiveness of strikes (James, Kelly, & Beckman, 2013).

Although research in MMA is growing, there is still a limited systematic comparison of isokinetic strength across

multiple joints and contractions among fighters. Most studies focus on isolated muscle groups or single contraction types, which restricts understanding of how different isokinetic parameters relate to explosive power crucial for MMA performance.

Understanding the relationships between muscle strength indicators may contribute to the optimization of testing protocols in combat sports and expand knowledge about optimizing power development in MMA. The aim of the study is to elucidate the relationships between explosive power of upper and lower limbs and isokinetic parameters such as time to peak torque and peak torque during concentric, eccentric, and isometric muscle contractions in MMA fighters.

Methods

Participants

The research sample included 17 male MMA fighters of national performance level. Their chronological age (median \pm quartile deviation) was 18.00 ± 1.00 years, their sports age was 3.001 years and they had completed 2.00 ± 1.50 fights. The weekly training load included five MMA sessions focused on striking (75 minutes), five jiu-jitsu sessions focused on grappling (75 minutes), and two weight sessions (60 minutes). General anthropometric characteristics are shown in Table 1.

Table 1. Anthropometrics characteristics of the research sample

	BH (cm)	BW (kg)	SMM (kg)	PBF (%)	BFM (kg)
Med\pmQD	178.90 \pm 3.80	72.30 \pm 6.05	36.62 \pm 3.07	8.70 \pm 1.75	6.10 \pm 1.35
Min/Max	164.70/186.80	53.40/81.40	25.30/44.61	3.00/14.30	2.20/10.50

Note. BH: body height; BW: body weight; SMM: skeletal muscle mass; PBF: percentage of body fat; BFM: body fat mass; VFA: visceral fat area; Med: median; QD: quartile deviation; Min: minimum value; Max: maximum value

Procedures and measurements

Before the measurements, participants were informed and consented to the purpose and procedures of testing, which was conducted in accordance with the Declaration of Helsinki (Harris, Macsween, & Atkinson, 2017). The research was approved by the ethics committee of the University of Presov (ECUP042025PO).

Basic anthropometric parameters of the research sample were measured by the BSM 170 stadiometer (Biospace, Seoul, North Korea) and by InBody 720 (Biospace, Seoul, North Korea) with focus on body weight, skeletal muscle mass, percentage of body fat and body fat mass. Subsequently, participants performed a 5-minute pretest warm-up on a cycle ergometer at a workload of 50 watts and a cadence of 80 rpm, followed by a 5-minute individualized segment comprising mobility and isometric exercises.

Explosive power was measured by Optogait (Microgate Srl, Bolzano, Italy). Standard countermovement push-up (SCPu), kneeling countermovement push-up (KCPu) and kneeling stop push-up (KSPu) tests were used to determine the explosive power of upper limbs. The reliability established by intra-class correlation coefficient (ICC) in relation to rate of force development is good for SCPu (ICC=0.77) and ex-

cellent for KCPu (ICC=0.90) and KSPu (ICC=0.93) (Dhahbi et al., 2017). For lower-body explosive power assessment, countermovement jump (CMJ), countermovement jump with free arms (CMJ FA), and squat jump (SJ) were used. The reliability of CMJ, CMJ FA, and SJ was established as excellent (ICC=0.997-0.998) (Glatthorn et al., 2011). All tests of explosive power consisted of three trials with one minute rest.

Time to peak torque (TTPT) and peak torque (PT) as indicators of isokinetic strength were measured by HUMAC NORM (Cybex NORM[®], Humac, CA, USA) focusing on the extensors and flexors of knee, hip, shoulder, and elbow joints in concentric, eccentric, and isometric muscle contractions in the dominant limb. Dominant limb was identified according to hemispheric lateralization using a limb-preference question collected during demographic data collection. The reliability of PT measurements by Cybex HUMAC NORM isokinetic dynamometer was established by intra-class correlation coefficient as excellent (ICC=0.90-0.98) (Impellizzeri, Bizzini, Rampinini, Cereda & Maffiuletti, 2008). During concentric and eccentric muscle contraction, muscle strength was measured in the range of motion 90° at angular velocity 60°·s⁻¹. An angular velocity of 60°·s⁻¹ was selected because lower testing velocities enable the expres-

sion of maximal PT and are widely recognized as a reliable standard for assessing maximal isokinetic strength (Kambič, Lainscak, & Hadžić, 2020). During isometric muscle contraction, muscle strength was measured in 60°. Isokinetic strength testing was conducted following the instructions predefined in the isokinetic dynamometer's software. Maximal elongation of tested limb was set as anatomical zero (0°). Testing consisted of two maximal-effort trials preceded by three submaximal-effort trials to familiarize participants with the test procedure. The best result of the two trials was selected for further analysis. Visual feedback and verbal motivation were provided during muscle strength testing on the isokinetic dynamometer to ensure maximal stimulation of moral-volitional qualities.

Statistical analysis

Based on the Shapiro-Wilk test for normality, non-parametric statistical methods were used for further analysis, and Spearman's correlation coefficient was used to determine correlations between selected parameters at $p < 0.05$ and $p < 0.01$. The effect size was estimated according to Cohen (1998) as follows: $0.1 \leq r < 0.3$ – small; $0.3 \leq r < 0.5$ – medium; $r \geq 0.5$ – large. Statistical analysis was performed using SPSS Statistics 27.0 software (IBM, Armonk, USA).

Results

The results of explosive power and isokinetic strength are shown in Table 2 and Table 3.

Table 2. Descriptive statistics of explosive power

	Med±QD Min/Max				
SCPu (cm)	KCPu (cm)	KSPu (cm)	CMJ (cm)	CMJ FA (cm)	SJ (cm)
10.90±2.20	46.60±20.90	39.90±15.00	36.30±3.00	43.50±1.95	33.90±3.65
4.90/22.10	19.30/67.70	15.90/55.10	22.60/47.00	27.20/53.70	23.60/43.10

Note. Med: median; QD: quartile deviation; Min: minimum value; Max: maximum value; SCPu: standard countermovement push-up; KCPu: kneeling countermovement push-up; KSPu: kneeling stop push-up; CMJ: countermovement jump; CMJ FA: countermovement jump with free arms; SJ: squat jump

Table 3. Descriptive statistics of isokinetic strength

	Med±QD Min/Max TTPT (s)					
	E con	E ecc	E iso	F con	F ecc	F iso
EL	0.64±0.18	1.08±0.25	1.75±0.63	1.21±0.22	0.87±0.16	2.30±0.44
	0.34/1.08	0.67/2.00	0.36/3.68	0.73/1.47	0.39/1.33	0.66/4.81
SH	0.49±0.12	1.40±0.19	1.81±0.62	0.46±0.36	0.70±0.17	1.43±0.54
	0.28/0.90	0.61/2.17	0.58/3.03	0.14/1.39	0.27/1.54	0.60/2.81
KN	0.52±0.10	1.11±0.17	2.61±0.45	0.53±0.13	0.96±0.19	1.67±1.05
	0.32/0.68	0.69/1.61	0.32/3.96	0.31/1.28	0.42/1.36	0.33/3.42
HI	0.39±0.09	1.34±0.20	3.10±0.54	0.42±0.19	0.72±0.20	1.76±0.54
	0.28/0.74	0.69/2.48	1.37/4.69	0.22/1.07	0.23/1.28	0.40/2.88
PT (n×m-1)						
	E con	E ecc	E iso	F con	F ecc	F iso
EL	39.00±6.50	46.00±8.00	42.00±9.00	50.00±12.50	65.00±12.00	73.00±15.50
	23.00/57.00	28.00/69.00	27.00/75.00	26.00/76.00	33.00/96.00	30.00/102.0
SH	100.00±16.0	108.00±18.5	113.00±12.5	58.00±13.00	81.00±21.00	73.00±5.00
	52.00/125.00	56.00/159.00	56.00/155.00	22.00/80.00	38.00/104.00	30.00/121.0
KN	220.0±19.00	221.00±39.5	259.00±40.0	117.00±9.50	125.00±19.50	121.00±13.50
	125.00/308.0	155.00/309.0	149.00/366.0	68.00/157.0	80.00/168.0	84.00/187.0
HI	255.00±40.00	304.50±58.00	297.00±51.00	144.50±21.007	141.50±16.508	130.50±10.50
	127.00/335.00	184.00/442.00	146.00/355.00	5.00/194.00	7.00/190.0	81.00/175.00

Note. Med: median; QD: quartile deviation; Min: minimum value; Max: maximum value; E: extensors; F: flexors; con: concentric; ecc: eccentric; iso: isometric; TTPT: time to peak torque; PT: peak torque; EL: elbow; SH: shoulder; KN: knee; HI: hip

The correlation analysis of upper-limb explosive power and isokinetic strength of the elbow and shoulder extensors and flexors is shown in Table 4.

Table 4. Correlations between explosive power of upper limbs and isokinetic strength of elbow and shoulder extensors and flexors

ELBOW	SCPu	KCPu	KSPu	SHOULDER	SCPu	KCPu	KSPu
E con TTPT	0.210	0.197	-0.055	E con TTPT	0.065	0.205	-0.094
E con PT	0.222	0.006	0.320	E con PT	0.463	0.259	0.405
E ecc TTPT	-0.082	0.126	0.116	E ecc TTPT	-0.054	0.017	-0.292
E ecc PT	0.256	0.028	0.361	E ecc PT	0.407	0.250	0.186
E iso TTPT	-0.015	0.075	0.376	E iso TTPT	0.287	0.297	0.490*
E iso PT	0.116	0.015	0.370	E iso PT	0.172	0.001	0.256
F con TTPT	-0.543*	-0.269	-0.012	F con TTPT	-0.365	-0.098	-0.172
F con PT	0.516*	0.269	0.284	F con PT	0.703**	0.422	0.332
F ecc TTPT	-0.054	0.076	0.033	F ecc TTPT	0.417	0.316	0.230
F ecc PT	0.542*	0.272	0.319	F ecc PT	0.630**	0.291	0.248
F iso TTPT	0.363	0.575*	0.327	F iso TTPT	-0.007	-0.242	-0.269
F iso PT	0.502*	0.236	0.299	F iso PT	0.509*	0.280	0.125

Note. SCPu: standard countermovement push-up; KCPu: kneeling countermovement push-up; KSPu: kneeling stop push-up; E: extensors; F: flexors; con: concentric; ecc: eccentric; iso: isometric; TTPT: time to peak torque; PT: peak torque; *: $p < 0.05$; **: $p < 0.01$

The correlation analysis showed that performance in the SCPu was significantly associated, with a large effect size, with the level of PT of elbow flexors during concentric ($r=0.516$, $p=0.034$), eccentric ($r=0.542$, $p=0.025$), and isometric ($r=0.502$, $p=0.040$) muscle contractions. In addition, the performance in the SCPu is significantly related, with a large effect size, to lower TTPT of elbow flexors during concentric muscle contractions ($r=-0.543$, $p=0.024$). Moreover, performance in the SCPu is significantly influenced, with a large effect size, by the level of PT of shoulder flexors in concentric ($r=0.703$, $p=0.002$), eccentric ($r=0.630$, $p=0.007$), and iso-

metric ($r=0.509$, $p=0.037$) muscle contractions. On the other hand, in relation to performance in the KCPu, results showed a significant association, with a large effect size, to higher TTPT of elbow flexors during isometric muscle contraction ($r=0.575$, $p=0.016$). Likewise, the results showed that performance in the KCPu significantly correlated, with a medium effect size, with higher TTPT of shoulder extensors during isometric muscle contraction ($r=0.490$, $p=0.046$).

The correlation analysis of explosive power of lower limbs and isokinetic strength of knee and hip extensors and flexors is shown in Table 5.

Table 5. Correlations between explosive power of lower limbs and isokinetic strength of knee and hip extensors and flexors

KNEE	CMJ	CMJ FA	SJ	HIP	CMJ	CMJ FA	SJ
E con TTPT	-0.316	-0.225	-0.295	E con TTPT	0.169	0.232	0.229
E con PT	0.573*	0.632**	0.685**	E con PT	0.612**	0.678**	0.615**
E ecc TTPT	0.055	-0.085	0.073	E ecc TTPT	-0.293	-0.178	-0.443
E ecc PT	0.470	0.559*	0.554*	E ecc PT	0.379	0.424	0.206
E iso TTPT	0.265	0.471	0.264	E iso TTPT	0.275	0.311	0.204
E iso PT	0.466	0.640**	0.571*	E iso PT	0.500*	0.562*	0.507*
F con TTPT	0.069	0.079	0.062	F con TTPT	0.081	0.082	0.010
F con PT	0.477	0.631**	0.652**	F con PT	0.411	0.486*	0.507*
F ecc TTPT	0.271	0.367	0.312	F ecc TTPT	-0.289	-0.213	-0.141
F ecc PT	0.701**	0.792**	0.749**	F ecc PT	-0.146	-0.123	-0.118
F iso TTPT	0.118	0.284	0.168	F iso TTPT	0.455	0.418	0.188
F iso PT	0.603*	0.750**	0.686**	F iso PT	-0.087	-0.029	-0.076

Note. CMJ: countermovement jump; CMJ FA: countermovement jump with free arms; SJ: squat jump; E: extensors; F: flexors; con: concentric; ecc: eccentric; iso: isometric; TTPT: time to peak torque; PT: peak torque; *: $p < 0.05$; **: $p < 0.01$

Based on the correlation analysis, the level of PT of knee extensors during concentric muscle contraction was significantly associated with performance in the CMJ ($r=0.573$, $p=0.016$), CMJ FA ($r=0.632$, $p=0.006$), and SJ ($r=0.685$, $p=0.002$), with a large effect size. Additionally, the level of PT of hip extensors during concentric muscle contraction was also significantly associated with performance in the CMJ ($r=0.612$, $p=0.009$), CMJ FA ($r=0.678$, $p=0.003$), and SJ ($r=0.615$, $p=0.009$), with a large effect size. On the contrary, the PT of knee flexors during concentric muscle contraction was significantly associated with performance in the CMJ FA ($r=0.631$, $p=0.007$) and SJ ($r=0.652$, $p=0.005$), with a large effect size. The PT of hip flexors during concentric muscle contraction was also significantly associated with performance in the CMJ FA, with a medium effect size ($r=0.486$, $p=0.048$), and with performance in the SJ, with a large effect size ($r=0.507$, $p=0.038$).

In relation to eccentric muscle contraction, statistically significant relationships with a large effect size were observed between PT of knee extensors and performance in the CMJ FA ($r=0.559$, $p=0.020$) and SJ ($r=0.554$, $p=0.021$). Additionally, PT of knee flexors was significantly associated, also with a large effect size, with performance in the CMJ ($r=0.701$, $p=0.002$), CMJ FA ($r=0.792$, $p<0.001$), and SJ ($r=0.749$, $p=0.001$). In terms of isometric muscle contraction, PT of knee extensors was significantly associated with performance in the CMJ FA ($r=0.640$, $p=0.006$) and SJ ($r=0.571$, $p=0.017$), with a large effect size. Likewise, PT of hip extensors was significantly related to CMJ ($r=0.500$, $p=0.041$), CMJ FA ($r=0.562$, $p=0.019$) and SJ ($r=0.507$, $p=0.038$), with a large effect size. On the contrary, PT of knee flexors during isometric muscle contraction was significantly associated with performance in CMJ ($r=0.603$, $p=0.010$), CMJ FA ($r=0.750$, $p=0.001$) and SJ ($r=0.686$, $p=0.002$), with a large effect size.

Discussion

Our study aimed to elucidate the relationships between explosive power and isokinetic parameters TTPT and PT in MMA fighters. The correlations between PT of upper and lower limb muscles and explosive power tests emphasize muscle strength's role in executing powerful movements, which are essential for MMA performance.

Regarding the upper limbs, statistically significant relationships with large effect sizes were observed between performance in SCPu and PT of elbow and shoulder flexors in concentric, eccentric, and isometric muscle contractions. In study by Zhou et al. (2023), strong correlations were found between shoulder internal rotation PT in concentric muscle contraction at an angular velocity of $60^\circ\cdot s^{-1}$ and maximal punch force in boxers. Moreover, shoulder internal rotation PT at an angular velocity of $180^\circ\cdot s^{-1}$ showed a stronger correlation with maximal punching force. These findings indicate that fighters with greater isokinetic strength in these areas can produce more powerful punches. The stronger associations observed for the SCPu may be due to the significantly higher mechanical and neuromuscular demands it places on the elbow and shoulder flexors compared to the kneeling variations. Consequently, SCPu performance more accurately re-

flects maximal upper-limb force-production capacity, making it a more sensitive indicator of the relationship between isokinetic strength and explosive pushing ability. In contrast, the KCPu and KSPu greatly reduce external loading and stability demands, which probably weaken these associations.

In terms of TTPT, correlation analysis showed that a lower TTPT of elbow flexors in concentric muscle contraction statistically correlated with a large effect size with performance in SCPu. However, higher TTPT of elbow flexors in isometric muscle contraction statistically correlated with performance in KCPu. It was also observed that higher TTPT of shoulder extensors positively influences performance in KSPu. Additionally, higher TTPT of shoulder extensors positively influenced performance in the KSPu. These findings support the notion that upper limb strength is essential for punching power and grappling efficiency, consistent with the research by García-Pallarés, López-Gullón, Muriel, Díaz and Izquierdo (2011). The limited influence of TTPT observed in our study may be attributed to several neuromechanical factors. Early-phase torque production is predominantly determined by quick neural activation, including motor unit recruitment speed and discharge rate modulation, which TTPT does not directly quantify (Del Vecchio, 2019). Furthermore, TTPT is measured under controlled isokinetic conditions, performed at a constant angular velocity, which does not replicate the multi-joint nature of explosive actions and is therefore not specific to MMA or other dynamic sport movements, which limits its ecological validity (Maffiuletti et al., 2016).

Our findings also revealed associations between isometric muscle contraction and explosive power of the lower limbs. Specifically, the PT of knee extensors showed a positive relationship with performance in the CMJ FA and SJ. Similarly, the PT of hip extensors was significantly linked to performance in CMJ, CMJ FA, and SJ. Moreover, the PT of knee flexors during isometric muscle contraction was associated with enhanced performance in all jump tests, further emphasizing the role of maximal strength in generating explosive movements. These results highlight the importance of both dynamic and static strength in lower-limb extensors for vertical jump performance. Our findings are consistent with Chen et al. (2023), who found significant correlations between PT of knee extensors at angular velocities of $60^\circ\cdot s^{-1}$, $180^\circ\cdot s^{-1}$, $240^\circ\cdot s^{-1}$, and CMJ performance in elite boxers, suggesting that PT in concentric contraction plays a crucial role in explosive jump performance. Moreover, the correlation between PT and vertical jump height in CMJ was the strongest at $240^\circ\cdot s^{-1}$. The study by Detanico, Pupo, Graup and Santos (2016) confirmed that isokinetic strength and vertical jump performance can distinguish between advanced and novice judokas, emphasizing the importance of concentric strength of the lower limb extensors. Furthermore, knee extension PT at an angular velocity of $60^\circ\cdot s^{-1}$ showed a stronger correlation with maximum punching force compared to PT at $180^\circ\cdot s^{-1}$ (Zhou et al., 2023). Interestingly, Hammami, Ouergui, Zinoubi, Zouita and Moussa, (2014) identified a significant relationship between PT and jump height in elite Tunisian taekwondo athletes, supporting the idea that PT and explosive performance are closely connected in various combat sports. More-

over, the study also did not observed a significant correlation between TTPT and jump height for angular velocities of 60°·s⁻¹ and 180°·s⁻¹. Strong correlations between PT of knee and hip extensors in concentric contraction and performance in CMJ, CMJ FA, and SJ indicate that PT in concentric contraction plays a crucial role in explosive jump performance. Our findings are supportive of findings by McErlain-Naylor, King and Pain (2014), who demonstrated that maximal isometric torque of knee extensors significantly contributes to the variability in jump height.

Our results showed significant associations between the PT of knee flexors and performance in CMJ, CMJ FA, and SJ. These findings suggest that eccentric strength of knee flexors is a critical determinant of explosive power. Similar conclusions were drawn by Nishiumi, Nishioka, Saito, Kurokawa and Hirose (2023), who conducted a systematic review examining the relationships between eccentric strength variables during jumping and lower limb eccentric strength in relation to vertical jump performance. This review emphasized that eccentric strength during the downward phase of CMJ and eccentric strength in movements such as squats and knee extensions are associated with jump height and reactive strength index. These findings suggest that enhancing eccentric strength of knee flexors through strength training may lead to increased explosive power, which is crucial for athletes in combat sports and other disciplines requiring lower limb strength.

The practical implications of our findings suggest that strength training for MMA fighters should emphasize the muscle groups and contraction modes that demonstrated significant associations with explosive performance. For the upper limbs, this includes concentric, eccentric, and isometric strength of the elbow and shoulder flexors, which were positively related to explosive push-up performance. For the lower limbs, enhancing concentric, eccentric, and isometric strength of the knee and hip extensors and flexors may improve vertical jump performance. Prioritizing contraction modes strongly associated with explosive outputs may therefore support more targeted performance-oriented strength development in MMA athletes.

It should be noted that our study has some limitations. The research did not include MMA fighters of all weight categories or a wider age range, which limits the generalizability of the findings to elite adult fighters. Therefore, it would be helpful to expand the research to include fighters of all weight categories and to increase the sample size. The main limitation of the study is the use of general tests of explosive power. General tests were selected because they minimize the influence of technical proficiency inherent to striking and grappling, allowing a clearer assessment of the fighters' underlying neuromuscular capabilities. In the future, it would be more appropriate to apply specific tests, such as punches against a punch sensor measuring impact force, for better ecological validity. Most research focuses on the isokinetic strength of the knee joint, so it was difficult to compare the findings in the hip, elbow, and shoulder joints. Since there is limited existing research on these muscle groups, the study could provide valuable insights and set a precedent for future research.

Conclusion

The findings of our study provide valuable insights into the relationships between isokinetic strength in concentric, eccentric, and isometric muscle contraction and explosive power in MMA fighters. The most notable relationships in the upper limbs were observed between the SCPu and PT of elbow and shoulder flexors, particularly during concentric, eccentric, and isometric muscle contractions. In the lower limbs, the most notable relationships were found between the PT of knee extensors and flexors and performance in CMJ FA and SJ during concentric, eccentric, and isometric muscle contractions, as well as between the PT of hip extensors in concentric and isometric contractions and performance in the CMJ, CMJ FA, and SJ. While PT proved to be a reliable predictor of explosive performance, TTPT did not appear to influence the quick execution of upper or lower-limb actions. This suggests that maximal strength capacity, rather than the speed of reaching peak force, may be more critical for power output in MMA fighters. Additionally, these findings provide coaches with guidance to optimize the development of explosive power by targeting key muscle groups, including the knee and hip extensors and elbow and shoulder flexors.

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial and financial relationships that could be construed as a potential conflict of interest.

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Performance Indicators in Elite Croatian Women's Handball: A Longitudinal Analysis

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Abstract

The analysis of performance indicators in modern sport has an increasingly important impact on a better understanding of trends in sports games, including handball. The aim of this study was to determine which defensive, offensive, and transition variables influence the final team ranking between successful and less successful teams. The analysis included a total of 3,044 matches of the First Croatian Women's Handball League (1st HRL) from 2011 to 2020, covering nine competitive seasons. Twenty seven variables describing offensive play, defensive play, transition phases, and goalkeeper performance were analyzed. Teams were classified as successful or less successful according to their final placement in the season. The results showed statistically significant differences between successful and less successful teams in the combination of the observed variables (Wilks' Lambda =0.47; $p<0.001$) for the absolute variables, and for the relative variables (Wilks' Lambda =0.50; $p<0.001$). Out of the 27 variables analyzed, 16 significantly differentiated the observed groups. The most important factor of success were: goalkeeper efficiency ($p=0.00$, $F=63.46$), shooting efficiency ($p=0.00$, $F=58.35$), accuracy of shots from outside positions 9 meters ($p=0.00$, $F=43.03$) and higher number of fast break attempts ($p=0.00$, $F=24.67$). The results of this study should serve as important guidelines for coaches and practitioners and contribute to the systematic development of young female handball players, with the aim of preparing future elite athletes.

Keywords: *match outcome, game impact, team quality, situational efficiency, fast break*

Introduction

Situational efficiency represents a partial indicator of the actual quality of a player and the game. It is conditioned by the individual and collective level of athletic performance, the degree of team coordination, and the overall preparedness of the player and team. In essence, statistics are used both to interpret past events and to guide a team's future decisions (Clemente et al., 2020). In practice, coaches often prioritize certain measures of situational efficiency based on their personal understanding of the game. Recent technologies have enabled the analysis of match record data, allowing for the quantitative assessment of various events and situations occurring during competition. Additionally, the content and flow of the match can be monitored and analyzed in real time, enabling timely adjustments to tactical and strategic decisions (Kim et al., 2008). Ideally, greater emphasis should be placed on factors that are most directly linked to winning (Foretić, 2012).

Currently, match analysis occupies a central position in scientific research aimed at monitoring and improving performance. Special interest in this topic is evident in numerous studies covering football (Beato, Youngs, & Costin, 2024) basketball (Gervasi et al., 2024), and water polo (Parezzetti et al. 2023). The theoretical understanding of performance in team sports can be enhanced by integrating frameworks such as Performance Profiling and Ecological Dynamics, which offer important perspectives on how situational factors interact with individual and collective behaviors to affect match outcomes. These models highlight the role of contextual constraints and team coordination, allowing for a more nuanced interpretation of performance in competitive settings.

Situational efficiency in handball has also been the subject of scientific research over the past few decades and plays an increasingly important role in the systematic monitoring, analysis, and improvement of competitive performance

(Foretic et al., 2021; Landure et al., 2019). Player and team actions in handball are recorded using advanced data collection systems, which have evolved significantly from the early manual video analysis methods (Gómez López et al., 2021; Prieto, Gómez, & Sampaio, 2015). Match analysis can be approached through two main levels of complexity: static and dynamic (Sampaio, Ibáñez, & Lorenzo, 2013). In the static approach, players' and teams' actions, as well as key events during the game, are recorded using notation systems (which were once manual but are now mostly automated). This method focuses on producing final match statistics while paying little or no attention to the situational context of the game at any given moment hence it is referred to as a structure-oriented model (Hatzimanouil et al., 2023; Krawczyk et al., 2022; Pfeiffer & Perl, 2006). While static analysis is valuable for descriptive and comparative purposes, it is inherently limited for understanding deeper causes of play outcomes. It can't capture the complex, adaptive, and context-dependent nature of decision-making in dynamic environments (Araújo et al. 2006). To overcome these limitations, static data should be complemented with temporal, spatial, and contextual analyses (e.g., sequential analysis, positional data, or constraint-based frameworks) that better reflect the realities of in-game decision processes.

Conversely to static, the dynamic approach records actions and significant events in direct relation to the ongoing flow of the match, capturing them in a chronological and sequential manner. This process-oriented model provides insight into how performance evolves throughout the game (Pfeiffer & Perl, 2006). The research we conducted was carried out using a static approach due to the complexity of collecting measurement data across a large number of matches.

A systematic review of the literature conducted in the field of handball on the topics of "match analysis," "performance analysis," "notational analysis," "game analysis," "tactical analysis," and "patterns of play" showed that most of the research was carried out using statistical data available from the tournament organizers. The focus of the studies was directed toward four main variables: total shots and finals, end match outcome, Time Outs (TTOs), and the relationship between home advantage (Landure et al., 2019; Pascual et al., 2024).

In this study, the final league ranking was used as the criterion of success because it represents an integrated and cumulative outcome of all matches played during the season and reflects the long term stability of team performance. Unlike goal difference, which can be strongly influenced by individual matches with large score margins, the final ranking better captures team consistency, efficiency, and the ability to adapt to different competitive contexts.

Scientific research on male handball is significantly more represented in the literature compared to female handball. A systematic review of scientific studies showed that 75% of the studies were conducted on male teams, while only 25% included female handball (Prieto, Gómez, & Sampaio, 2015). The lack of longitudinal research is particularly pronounced in female handball. The only longitudinal comparative analysis conducted between 2017 and 2021 across four major international competitions identified variables that significantly

influence match outcomes: shooting efficiency from 6 and 9 meters, goalkeeper saves, number of goals from fast breaks, and number of steals (Park et al., 2021).

Longitudinal studies have most often been conducted on major tournaments, whereas research on professional leagues over multiple seasons is rare. For example, in the Swedish Women's First League over two seasons, short periods of better or worse performance in situational parameters were observed (Moesch et al., 2014). Therefore, our study contributes to the understanding of situational efficiency in female handball within a league system.

The aim of this study is to conduct a longitudinal analysis of situational parameters across nine competitive seasons in the Croatian Women's Handball League and to determine which defensive, offensive, and transition variables influence the final team ranking between successful and less successful teams.

Materials and methods

Participants and design

The research was conducted over the period from 2011 to 2020, covering nine competitive seasons. A total of 3,044 matches were analyzed, including all matches of the 1st Croatian Women's Handball League (1. HRL) in the national championship. The analysis was performed on a large portion of the data recorded in defense, offense, and transitions. Players' identities were anonymized following the principles of the Declaration of Helsinki to ensure confidentiality.

Procedures

Data were collected from the official website of the Croatian Handball Federation (HRS). A software program for data collection was developed based on the TOMASOFT platform, which is used for analysis and processing of data. During each match, an official entered the recorded data into a software system according to the situational events occurring in the game. All recorded results were immediately processed and subsequently recorded and stored in the database.

Variables

For the purposes of this study, 27 variables were used in a previous study conducted on a sample of male handball players in the 1st Croatian Handball League (Bajgorić et al., 2017). All variables are part of the system employed by the Croatian Handball Federation (HRS) and are applied in all matches of the national championship. The sample of variables included relative variables expressed as percentages (%): SHT % (shot efficiency), 7M % (7 metre throw efficiency), OUT % (outside shot accuracy), 6M % (6-metre shot accuracy), FB GLS % (fast break efficiency), AST % (assist efficiency), and GS % (goalkeeper save percentage). The absolute variables included: TOT SHT (total shots attempted), GLS (goals scored), TOP GLS (most goals scored in a game), 7M ATT (7 metre throws attempted), 7M GLS (7 metre goals scored), OUT ATT (outside shots attempted), OUT GLS (outside shot goals), 6M ATT (6 metre shots attempted), 6M GLS (6 metre goals), FB ATT (fast break shots attempted), FB ATS (fast break attempts),

AST (assists), TO (turnovers), TO/G (turnovers per game), STL (steals/interceptions), STL/G (steals per game), SUS (suspensions), SUS/G (suspensions per game), GOLKSHT (shots faced by the goalkeeper), and GOLKSAV (goalkeeper saves).

mality assumptions. The level of statistical significance was set at $p < 0.05$. Statistical analysis was carried out using Statistical Package Software for Social Science, version 28 (SPSS Inc., Chicago, IL, USA).

Statistics

For the description of the basic characteristics of the analyzed variables, descriptive statistics was used (mean, minimum, maximum, standard deviation, skewness, kurtosis, Max D). The normality of variable distributions was examined using the Kolmogorov–Smirnov test. Differences between successful and unsuccessful teams were first examined using multivariate analysis of variance (MANOVA) with the application of Wilks’ Lambda. After establishing multivariate significance, univariate analyses of variance (ANOVA) were conducted for variables with normal distributions, while the Kruskal–Wallis test was used for variables with violated nor-

Results

Table 1 presents the results of descriptive statistics for all variables included in the analysis of the observed situational parameters. The results indicate that, unlike the other variables which show a normal distribution, four variables deviate from normality: 7M ATT (Max D=0.45), 7M GLS (Max D=0.40), STL (Max D=0.18), and STL/G (Max D=0.18). The normality of variable distributions was examined using the Kolmogorov–Smirnov test, with the criterion values for deviation from normal distribution set at Max D=0.12 at the significance level of $p < 0.10$, and Max D=0.15 at the significance level of $p < 0.05$.

Table 1. Descriptive statistics of examined variables

VAR	AM	Min	Max	SD	Skew	Kurt	Max D
TOT SHT	1023.75	394.00	1384.00	202.92	-1.10	1.11	0.15
GLS	584.22	198.00	888.00	127.71	-0.64	0.89	0.07
SHT %	57.49	43.61	71.84	5.70	0.17	-0.18	0.06
TOP GLS	26.40	18.64	56.79	4.56	2.83	15.73	0.13
7M ATT	173.20	33.00	1281.00	271.31	3.34	9.61	0.45
7M GLS	112.46	24.00	713.00	140.04	3.33	9.88	0.40
7M %	74.05	49.14	87.96	7.95	-1.12	1.65	0.11
OUT ATT	419.66	153.00	665.00	114.79	-0.24	-0.65	0.07
OUT GLS	176.00	67.00	275.00	45.21	-0.20	-0.49	0.07
OUT %	42.30	27.68	57.30	5.72	0.17	0.08	0.05
6M ATT	236.99	92.00	562.00	64.12	0.92	5.25	0.11
6M GLS	171.30	55.00	345.00	46.11	0.30	1.51	0.08
6M %	72.36	51.07	82.14	4.72	-0.79	2.43	0.05
FB ATT	59.26	7.00	197.00	35.72	1.19	1.70	0.12
FB ATS	46.68	4.00	158.00	28.53	1.17	1.83	0.11
FB GLS%	78.30	54.55	97.22	7.85	-0.72	0.76	0.09
AST	2.92	0.41	10.18	2.00	1.42	2.13	0.13
AST %	64.68	8.00	240.00	46.03	1.40	2.26	0.12
TO	218.76	23.00	382.00	77.08	-0.22	-0.55	0.06
TO/G	9.46	1.83	14.69	2.60	-0.45	-0.04	0.05
STL	46.17	1.00	176.00	35.13	1.98	4.52	0.18
STL/G	1.98	0.06	7.86	1.43	2.08	5.12	0.18
SUS	67.11	16.00	103.00	17.55	-0.39	-0.17	0.08
SUS/G	3.01	1.63	9.72	0.82	4.35	35.34	0.14
GOLSHT	837.79	258.00	1137.00	171.99	-1.17	1.81	0.12
GOLSAV	251.26	74.00	421.00	70.54	-0.16	-0.50	0.05
GS %	29.91	17.99	43.38	5.90	0.22	-0.23	0.06

Note. VAR: variable; AM: arithmetic mean; Min: minimum value; Max: maximum value; SD: standard deviation; Skew: asymmetry coefficient; Kurt: distribution curvature coefficient; MaxD: maximum difference between real and theoretic cumulative frequencies

Table 2 presents the results of the multivariate analysis of variance (MANOVA) conducted to examine differences between successful and unsuccessful teams for both absolute and relative variables. In both cases, similar results were obtained, with statistically significant differences observed for

the absolute variables (Wilks' Lambda =0.47, $p < 0.001$) as well as for the relative variables (Wilks' Lambda =0.50, $p < 0.001$). The low p values ($p < 0.001$) in both analyses confirm that the observed differences are highly statistically significant.

Table 2. Multivariate analysis of variance (MANOVA)

Multivariate analysis (MANOVA) of variance between successful and unsuccessful teams using only absolute variables				
Wilks λ	Rao's R	df1	df2	p
0.47	6.17	19	103	0.00
Multivariate analysis of variance (MANOVA) between successful and unsuccessful teams using only relative variables				
Wilks λ	Rao's R	df1	df2	p
0.50	14.34	8	114	0.00

Note. Wilks λ : Wilks' Lambda; Rao's R: F-approximation of the Hotelling–Lawley trace (U); df1:degrees of freedom 1; df2: degrees of freedom 2; p - coefficient of significant difference $p < 0.05$.

Table 3 presents the results of the univariate analysis of variance (ANOVA) for all variables and the Kruskal–Wallis test for variables with non-normal distributions between successful and less successful teams. Out of a total of 27 variables, 16 showed a statistically significant difference. The results showed that the variable GS% ($p = 0.00$, $F = 63.64$) was the most important factor distinguishing between the two observed qualitative groups. The second most important variable was SHT% ($p = 0.00$, $F = 58.35$), indicating that shooting efficiency plays a crucial role and is likely correlated with

the previous variable, as well as with the contribution of goalkeepers through saves. The outside shooting percentage OUT% ($p = 0.00$, $F = 43.03$) also significantly contributed to the differences between successful and less successful teams. Furthermore, transition play, which is often a product of effective defensive reactions, was reflected in the variable fast break attempts FB ATS ($p = 0.00$, $F = 24.67$), which proved to be statistically significant and made a substantial contribution to the differences between the two qualitative groups.

Table 3. Univariate analyses of variance (ANOVA) for variables with normal distribution and Kruskal–Wallis test or variables with violated normality assumptions

VAR	SUCC AM	LS AM	F	p	H	p
TOT SHT	1037.10	1009.73	0.56	0.46		
GLS	626.48	539.85	15.86	0.00		
SHT %	60.65	54.18	58.35	0.00		
TOP GLS	28.14	24.58	22.03	0.00		
7M ATT	152.56	194.87	0.75	0.39	0.78	0.38
7M GLS	103.03	122.37	0.58	0.45	0.64	0.42
7M %	75.21	72.84	2.79	0.10		
OUT ATT	398.67	441.70	4.44	0.04		
OUT GLS	179.03	172.82	0.58	0.45		
OUT %	45.15	39.31	43.03	0.00		
6M ATT	249.13	224.25	4.77	0.03		
6M GLS	185.19	156.72	12.86	0.00		
6M %	74.22	70.41	23.82	0.00		
FB ATT	73.52	44.28	24.58	0.00		
FB ATS	58.10	34.70	24.67	0.00		
FB GLS %	79.43	77.12	2.68	0.10		
AST %	76.29	52.50	8.72	0.00		
AST	3.49	2.31	11.69	0.00		

(continued from previous page)

Table 3. Univariate analyses of variance (ANOVA) for variables with normal distribution and Kruskal–Wallis test or variables with violated normality assumptions

VAR	SUCC AM	LS AM	F	p	H	p
TO	211.56	226.33	1.13	0.29		
TO/G	9.03	9.92	3.74	0.06		
STL	54.46	37.47	7.58	0.01	2.08	0.15
STL/G	2.31	1.64	7.11	0.01	2.70	0.10
SUS	70.54	63.52	5.09	0.03		
SUS/G	3.21	2.80	8.04	0.01		
GOLKSHT	809.52	867.47	3.56	0.06		
GOLKSAV	270.13	231.45	9.91	0.00		
GS %	33.28	26.38	63.46	0.00		

Note. VAR: variable; AM: arithmetic mean; Min: minimum value; Max: maximum value; SD: standard deviation; Skew: asymmetry coefficient; Kurt: distribution curvature coefficient; MaxD: maximum difference between real and theoretic cumulative frequencies

Discussion

This study has several important findings: 1) the goalkeeper's save percentage is the most significant situational parameter for final success in women's handball, 2) shot efficiency has an important impact on the final ranking, 3) outside shot accuracy significantly contributes to the difference between successful and less successful teams, 4) transition play in handball has an increasingly important influence on the game in terms of the number of attempts.

The save percentage of goalkeepers emerged as the most important factor for the final ranking of the team. The role of the goalkeeper in handball is such that achieving top results is very difficult without their contribution in terms of both percentage and number of saves. An interactive approach, often involving two or three goalkeepers participating in matches with their saves, has proven to be an effective strategy for winning top table positions. An increase in the goalkeeper's save percentage of approximately 6% in our research can have a significant impact on the probability of winning. Consequently, even relatively small differences in save percentage can have a substantial cumulative effect on individual match results and the team's final ranking (Gómez López et al., 2021). Comparisons with European Championships between 2018 and 2020 showed a variation percentage of 30–33% for men and 33–36% for women (Bojić-Čačić, 2021). The highest save efficiency for both genders was observed for shots from nine meters and toward the central parts of the goal, while the least successful saves were from fast break shots and shots directed toward lower and side zones. Overall, female goalkeepers achieved a higher percentage of stopped shots regardless of shot position or goal zone (Gómez López et al., 2021). Research conducted by Hianik (2011) in Slovakia using the computer program Assessment Game Performance in Team Handball on first-league players showed that the number of saves from different positions significantly contributes to the final match result. Goalkeepers achieve more saves from outside positions, which can be attributed to more effective

collaboration between defensive players and the goalkeeper (Park et al., 2021). Research conducted on a sample of male and female handball goalkeepers who participated in the 2020 European Handball Championship in Denmark showed that the save percentage is equally important for men (-0.34) and women (-0.32) (Foretic et al., 2021). This result is consistent with the findings of Hansen et al. (2017), who stated that the save percentage is a key factor for achieving a better team ranking. Their results indicated a moderate but statistically significant negative correlation between goalkeeper efficiency and the team's final placement ($R^2=0.464$, $p<0.001$, $r=-0.68$; 95% CI: -0.85 to -0.38). The analysis confirmed that goalkeeper efficiency in matches is one of the most reliable indicators of a team's final success in major tournaments or national championships. The reasons for these results can be attributed to the goalkeeper's role, as the goalkeeper occupies a central position in the structure of handball play and is the only player who directly prevents goals, thereby exerting an immediate influence on the match outcome. Also, each successful save, in addition to its defensive value, often creates conditions for a rapid transition to attack and the execution of fast breaks.

Shot efficiency is an important variable that differentiates successful and less successful teams. It is certainly associated with the percentage and number of goalkeepers saves. The results of our research show that the average success rate of successful teams was 60.65%. These results align with similar studies. For example, research by Krawczyk et al. (2022) on the Women's Handball European Championship 2022 showed that winning teams scored a significantly higher number of goals in attack ($d=1.43$) and had higher attack efficiency ($d=1.71$). Evaluation of data from four Olympic tournaments (2004–2012) for women indicated that, in addition to goalkeeper saves, technical errors, steals, and shot efficiency have a major impact (Saavedra et al., 2018). Offensive efficiency trends are one of the most important predictors of team success. Longitudinal research in men's handball at World Championships (2011–2019) showed an increase of 19.5% when peak efficiency reached 57.5% (Landure et al.,

2019). Research by Foretić (2012) indicated that teams scored an average of 28.17 goals per match, while more recent studies show this number slightly higher at 30.10 goals per match for top teams (Panagiotis et al., 2020). Shot efficiency significantly influences goal-scoring outcomes, distinguishing more successful teams from less successful ones. Higher shot efficiency is associated with fewer goalkeeper saves and technical errors, thereby enhancing competitive performance. These findings are consistent with previous research, indicating that superior offensive efficiency predicts improved outcomes in international handball competitions (Park et al., 2021).

Outside shooting accuracy is a very important parameter of situational efficiency identified in our study. Research analyzing match play shows that a large proportion of shots are taken from distances of 9 m or more (outside zone); however, the efficiency of these shots is lower compared to shots taken from closer positions (Smolarczyk, 2023). Our research indicated that the average percentage of long range shots from beyond 9 m or more was 45.15% among successful teams. In one analysis, 65.6% of all shots in matches were taken from the outside zone (9 m or more), with an average efficiency of approximately 38–40%, suggesting that these shots still represent an important factor in a team's overall scoring efficiency (Hatzimanouil et al., 2017). Recent trends in offensive structure at the EHF EURO 2020 and 2022 indicate a decrease in the number of shot attempts from the 9 m distance over time, accompanied by an increase in shots taken from closer positions, which reflects tactical changes in modern men's handball (Smolarczyk, 2023). In women's handball, an analysis of five World Women's Handball Championships from 2009 to 2017 showed that technical–tactical variables, including the efficiency of shots from 9 m, improved over successive competitions (Skoufas, 2019). In a comparative analysis of international competitions involving 12 national teams that participated in the Tokyo 2021 Olympic Games, the success rate of 9 m shots was among the indicators that had a positive impact on match outcomes, together with other performance variables (Park et al., 2021). Furthermore, an analysis of the three best women's national teams France, Russia, and Norway at the Tokyo Olympic Games revealed that their style of play was primarily based on shots from 9 m and shots from 6 m. These findings indicate that the aforementioned variables significantly determine offensive performance in modern women's handball (Bajgorić & Đug, 2022). The observed results can be attributed to the fact that outside shooting accuracy directly affects overall offensive efficiency, even though the effectiveness of these shots is lower than that of closer range attempts. The high proportion of shots taken from the 9 m zone indicates that, despite lower individual efficiency, these attempts still contribute substantially to total goals scored and influence the tactical structure of the attack. Moreover, improvements in technical tactical performance and the increased use of closer range shots, demonstrate that these variables play a critical role in determining offensive performance in modern women's handball and significantly impact match outcomes (Saavedra et al., 2018).

The acceleration of play in handball matches, due to rule changes, improved physical preparation of teams, and tran-

sition to attack (including fast breaks, individual and group counterattacks, and extended counterattacks) against unstructured zone defense, where space-time intervals are maximally exploited, has become an increasingly important factor in modern handball. According to Yiannakos et al. (2005), who analyzed matches of the Greek national championship in 2003, the frequency of fast break shots was higher in the first half (56.1%) than in the second half (43.9%), and conversion was better in the first half (77.1%) compared to 66.9% in the second half, likely due to player fatigue toward the end of the match. These findings are consistent with Hatzimanouil et al. (2023), who demonstrated that 38% of the game was related to fast-break execution, which is a key factor for predicting team success at the EHF EURO 2022. Similarly, Gutierrez et al. (2011) conducted a discriminant analysis to identify differences between winning and losing teams in the 2008–2009 season Asobal league Spain. Results showed that winning teams scored more goals on average from all shooting distances. The most pronounced differences, however, were observed in fast-break goals and attempts, which were the only shooting statistics that significantly distinguished successful from unsuccessful teams. A similar study conducted on the Croatian Men's Premier League (Bajgorić et al., 2017) found that level of significance, average number of goals from counterattacks ($p=0.00$), and average number of shots from counterattacks ($p=0.02$) were important for team success in the final ranking. In women's handball, fast break efficiency was also shown to be crucial. Ohnjec et al. (2003) found that fast break goals significantly contributed to goal difference at the 2003 Women's World Championship in Croatia, with successful teams using this tactic more frequently to score “easy goals” compared to losing teams. Recent research on performance indicators at the 2022 European Women's Handball Championship shows that teams achieving a higher number of fast break attempts are statistically more likely to win matches (Krawczyk, 2025). Fast break actions in modern handball constitute a critical determinant of team success, as they enable the exploitation of unstructured defensive formations and the creation of high-percentage scoring opportunities. The frequency and effectiveness of fast breaks are typically higher in the first half of matches, reflecting optimal player freshness, whereas fatigue in later stages of play reduces execution efficiency. Empirical analyses consistently demonstrate that teams that utilize fast break strategies more frequently achieve superior performance outcomes and exhibit a higher likelihood of winning, a trend evident in both men's and women's handball competitions (Landure et al., 2019).

Despite the relevance of the findings, this study has some limitations that should be acknowledged. First, the analysis was based on situational performance indicators derived from official match statistics, which may not fully capture the dynamic, contextual, and tactical interactions occurring during the game. Second, potential confounding factors such as team quality, coaching strategies, player injuries, and in match contextual variables (e.g., match status or opponent strength) were not explicitly controlled.

All above mentioned findings align with previous studies, and the strength of this research lies in the wide range of

situational parameters analyzed. Future research should be based on longitudinal analyses of multiple consecutive major international competitions in order to systematically monitor changes in tactical and performance related trends in women's handball, with particular emphasis on the proportion of 9m shots, outside shooting efficiency, and the evolution of offensive playing patterns. Furthermore, the application of advanced statistical and analytical approaches, including multilevel modeling and time series analysis, is recommended to enable more robust modeling of match outcomes, more accurate prediction of competitive success, and a deeper understanding of the interdependencies and dynamic relationships among situational performance indicators.

Conclusions

The results of this study confirm that goalkeeper save percentage, shot efficiency, outside shooting accuracy, and transition play represent key situational performance indicators of success in elite women's handball. Goalkeeper efficiency emerged as the most influential factor, highlighting its decisive role in match outcomes and final rankings. In addition, offensive efficiency particularly in positional and outside shooting along with an increased frequency of fast-break attempts, significantly differentiates winning from losing teams. These findings are consistent with previous research and underline the growing importance of transition play in modern women's handball. Overall, the comprehensive analysis of situational parameters provides valuable insights for performance optimization and supports evidence based approaches to training and tactical preparation. Therefore, coaches should structure training to develop tactical skills as well as physical, physiological, and psychological readiness to sustain a high playing tempo. In the long term, these success indicators should guide the development of young female handball players to prepare future elite athletes.

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Conflicts of interest

The authors declare no conflict of interest.

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Examination of the Relationship Between Attitudes Towards Healthy Nutrition and Sleep Quality: The Role of Lifestyle Factors

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Abstract

The relationship between lifestyle factors such as sleep quality and dietary habits has attracted growing interest due to their combined influence on overall well-being. Poor sleep quality has been linked to impaired cognitive functioning and emotional regulation, which may contribute to less healthy food choices, whereas a nutritious diet can support better sleep. This study examined the associations between sleep quality and attitudes toward healthy nutrition among adults living in Türkiye and explored how lifestyle factors (physical activity, smoking, alcohol consumption) relate to these variables. A convenience sample of 358 adults completed an online survey. Of the 358 survey responses collected, 346 were deemed valid and included in the final analysis after excluding 12 unsuitable entries. Sleep quality was assessed using the Pittsburgh Sleep Quality Index (PSQI), and attitudes were measured with the Attitudes Towards Healthy Nutrition Scale (ASHN). A weak negative correlation was found between sleep quality and attitudes toward healthy nutrition ($r=-0.205$, $p<0.001$), indicating that approximately 4% of the variance in nutrition attitudes was explained ($r^2=0.042$). Similar weak negative correlations were observed across the ASHN subdimensions. In addition, lifestyle factors were associated with both sleep quality and nutrition attitudes; notably, daily physical activity demonstrated a moderate association with ASHN ($\eta^2=0.108$). Public health initiatives that incorporate sleep hygiene education may be modestly associated with more positive nutrition-related attitudes, but the small effect size indicates that sleep should be considered only one minor component within broader, multifactorial interventions targeting diet, physical activity, emotional regulation, and other aspects of healthy living.

Keywords: *sleep health, diet quality, physical activity, health behaviours, exercise*

Introduction

The increasing awareness of the interplay between lifestyle factors and health outcomes has directed considerable attention to the relationship between attitudes towards healthy nutrition and sleep quality. The relationship between diet and sleep quality affects people uniquely because their special eating habits alongside sleep behaviours strongly affect their well-being (Abu Jamous et al., 2024; Hudson et al., 2007; Scarapicchia et al., 2015; Whatnall et al., 2020). Diet quality has been consistently linked with mental health outcomes, where

healthier dietary patterns are associated with a reduced risk of depression and anxiety (Lassale et al., 2019; Li et al., 2017; Molendijk et al., 2018). Studies demonstrate that eating foods with many vitamins and minerals helps the body control sleep cycle rhythms and enhances sleep quality (Burrows et al., 2020; Dashti et al., 2015; Zuraikat et al., 2021). Eating can affect sleep patterns, thus making dietary influences on health more complicated (Ghani et al., 2022; St-Onge, 2017; Wilson et al., 2022). Dietary choices play an essential role in sleep quality because high-fat and high-sugar diets have been proven to cause dete-

riorating sleep quality (AlKasasbeh et al., 2024; Chaput et al., 2023; Dashti et al., 2015; Wilson et al., 2022).

Sleep quality has emerged as a crucial determinant of physical and psychological health, with poor sleep being closely linked to higher levels of psychological distress and impaired cognitive function (Dietrich et al., 2016; Freeman et al., 2017; Semsarian et al., 2021). Insufficient sleep and circadian misalignment contribute to obesity, demonstrating a complex interplay between sleep and dietary behaviours (Al-Khatib et al., 2017; Chaput et al., 2023; Konttinen, 2020). Furthermore, sleep deprivation can lead to increased appetite and caloric intake, particularly from high-calorie foods, exacerbating weight gain and metabolic disorders (Al-Khatib et al., 2017; St-Onge et al., 2012; Zuraikat et al., 2021).

Scientific research reveals that sleep directly impacts dietary habits, although dietary habits also affect sleep patterns (Godos et al., 2021; Zuraikat et al., 2021). Inadequate sleep patterns often cause people to select unhealthy foods, intensifying sleep problems and forming a harmful cycle that negatively impacts their health (Huang et al., 2021; Fenton et al., 2021; Kline, 2014). This bidirectional relationship is evident in studies showing that poor sleep can increase cravings for high-calorie foods and lead to emotional eating, further impacting body weight and overall health (St-Onge et al., 2012; Penaforte et al., 2019; Van Strien & Koenders, 2014). Stress and anxiety serve as psychological and emotional factors that transmit signals between diet changes and disrupted sleep events, thus advocating for broad-based investigations of these behaviours (Goldstein & Walker, 2014; Konttinen et al., 2019; Richards & Specker, 2021).

The interplay between sleep quality and dietary habits is further influenced by various socio-demographic factors such as age, gender, and socio-economic status, which play a significant role in shaping both nutrition and sleep behaviours among different populations (Adams et al., 2017; Orhan et al., 2025; Whatnall et al., 2020). The stress on overall health will be affected by how socio-economic inequalities influence people's ability to access nutritious food along with proper sleep practices (Australian Bureau of Statistics, 2015; Hayes et al., 2019; World Health Organization, 2020). Furthermore, geographic variations also play a role, with differences in obesity prevalence and associated risk factors observed across different regions and populations (Gong et al., 2018; Samouda et al., 2018).

This study examines the relationship between sleep quality and attitudes toward healthy nutrition among adults living in Türkiye. Specifically, it aims (a) to investigate the associa-

tion between global sleep quality and overall attitudes toward healthy nutrition, (b) to examine how sleep quality relates to specific sub-dimensions of attitudes toward healthy nutrition, and (c) to explore whether attitudes toward healthy nutrition differ according to key lifestyle factors such as physical activity, smoking, and alcohol consumption. By clarifying these relationships, the study seeks to provide a focused empirical basis for designing health promotion strategies that consider sleep, diet, and lifestyle as interconnected components of well-being.

Materials and methods

Relational research aims to determine whether two or more variables change together and, if they do, how this change occurs (Fraenkel et al., 2012). In this study, the relational research method, one of the quantitative research methods, was used. This method, used to examine whether two or more variables affect each other (Tekbıyık, 2023), was employed to investigate whether there is a relationship between individuals' sleep quality and their attitudes towards healthy nutrition.

Study group

A convenience sampling method was used in the study, and the sample consisted of individuals who voluntarily agreed to participate. In a convenience sampling approach, individuals included in the research are not selected randomly from a defined sampling frame; participation is limited to volunteers who respond to the researcher's announcement (Stratton, 2021). Therefore, a probabilistic selection process was not implemented in this study, no random sampling from the target population was conducted, and the representativeness of the sample remained limited. This is considered one of the methodological limitations of the research.

The sample size was determined in line with the recommendation of having 15–20 observations per independent variable for correlation analyses (Akbulut & Çapık, 2022), and the study aimed to reach more than 250 participants (Schönbrodt & Perugini, 2018). Responses were obtained from a total of 358 participants; after data cleaning, 12 unsuitable responses were excluded, and the analyses were carried out with 346 participants. The frequency and percentage distributions of participants' gender, educational level, employment status, health behaviours, and other demographic characteristics are presented in Table 1.

Table 1. Demographic characteristics of the participants

Demographic Information		f	%
Gender	Female	231	66.76
	Male	115	33.24
Educational Status	High School and below	232	67.05
	University and above	114	32.95
Employment Status	Employed	139	40.17
	Unemployed	207	59.83

(continued from previous page)

Table 1. Demographic characteristics of the participants

Demographic Information		f	%
Having an Athlete's License	Yes	185	53.47
	No	161	46.53
Regular Health Check-Ups	Yes	101	29.19
	No	245	70.81
	None	36	10.40
Daily Physical Activity	1-2 days per week	83	23.99
	3-4 days per week	147	42.49
	5-6 days per week	59	17.05
	Every day	21	6.07
Sleep Pattern	Regular	80	23.12
	Irregular	111	32.08
	Sometimes regular, sometimes irregular	155	44.80
Family History of Genetic Diseases	Yes	59	17.05
	No	236	68.21
	Does not know	51	14.74
Smoking Status	Never smoked	169	48.84
	Used to Smoke, but Quit	49	14.16
	Smokes less than 10 cigarettes a day	55	15.90
	Smokes 10 or more cigarettes a day	73	21.10
Alcohol Consumption	Never consumed	155	44.80
	A few times a month	163	47.11
	A few times a week	28	8.09

Data collection tool

The research used three data collection tools: the “Demographic Information Form” to gather information about individuals, the “Pittsburgh Sleep Quality Index (PSQI),” and the “Attitudes Towards Healthy Nutrition Scale (ASHN)”.

Pittsburgh Sleep Quality Index (PSQI)

The PSQI, developed by Buysse et al. (1989) to assess sleep quality, was validated and adapted to the Turkish language by Ağargün et al. (1996). The PSQI measures sleep quality across seven subcomponents: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep medication, and daytime dysfunction. The PSQI has been used to evaluate sleep quality over the past month. The PSQI consists of seven components and 24 questions. Of these 24 questions, 19 are self-assessment questions, while the other five are to be answered by the participant's spouse or roommate. These five questions, which the spouse or roommate answers, are for clinical information purposes only and are not included in the score calculation. In this study, the five questions to be answered by the spouses or roommates were excluded from the research process. The self-assessment questions include various dimensions related

to sleep quality. Each item is scored between 0 and 3 points, and the sum of the seven component scores constitutes the total PSQI score. The total score on the scale ranges between 0 and 21. A total PSQI score of ≤ 5 indicates good sleep quality, while a score of > 5 indicates poor sleep quality. In the reliability study of the Turkish form of the scale, Cronbach's alpha internal consistency coefficient was calculated as 0.80 (Ağargün et al., 1996).

Attitudes Towards Healthy Nutrition Scale (ASHN)

The Attitudes Towards Healthy Nutrition Scale (ASHN) was developed by Tekkurşun Demir and Cicioğlu (2019). The ASHN consists of four factors and 21 items. The factors are named Information on Nutrition (IN), Emotion for Nutrition (EN), Positive Nutrition (PN), and Malnutrition (MP). The minimum score obtained from the ASHN is 21, and the maximum score is 105. A score of 21 indicates a very low attitude towards healthy nutrition, 23-42 indicates a low attitude, 43-63 indicates a moderate attitude, 64-84 indicates a high attitude, and 85-105 indicates an ideal, high attitude towards healthy nutrition.

When the analyses related to the scale were examined, the Kaiser-Meyer-Olkin (KMO) test result in the exploratory

factor analysis was found to be 0.87, and the Bartlett Sphericity test's chi-square value was 5076.914 ($df=476$; $p<0.001$). The scale explains 57.79% of the total variance. It was found that the factor loadings of the factors in the measurement tool were higher than 0.40. The factor loadings of each item in the scale ranged between 0.41 and 0.95. In the results of the confirmatory factor analysis of ASHN, the fit index values obtained were $\chi^2/df=1.71$, RMSEA=0.04, PGFI=0.74, PNFI=0.82, GFI=0.92, AGFI=0.90, IFI=0.98, NFI=0.95, and CFI=0.98. The internal consistency coefficient and the test-retest method examined the scale's reliability. Accordingly, the internal consistency coefficients were found to be 0.90 for IN factor, 0.84 for EN factor, 0.75 for PN factor, and 0.83 for MP factor. The reliability coefficient for the test-retest was calculated as 0.81, 0.79, 0.68, and 0.80, respectively. No item was removed due to the item analysis, and it was determined that all the items in the scale were distinctive. Additionally, it was found that the item-total correlation values ranged between 0.68 and 0.92. Based on all these analyses, it was concluded that the ASHN is a valid and reliable measurement tool that can be used to assess university students' attitudes towards healthy nutrition.

Data collection procedure and data analysis

The study data were collected using an online questionnaire prepared in line with the aim of the research and admin-

istered electronically. The scale items and the personal information form were transferred to the online environment, and the survey link was shared in various social media groups and communication networks accessible to the researcher. In the first part of the form, participants read and approved an informed consent text explaining the purpose of the study, the principle of voluntary participation, and confidentiality conditions; only after providing consent were they directed to the questionnaire. The data collection process resulted in a total of 358 completed forms. The IBM SPSS Statistics software (Version 27.0; IBM Corp., Armonk, NY, USA) was used to analyse the collected data. Before starting the analysis, the scores obtained from the scales were calculated and the assumptions of normality were examined. First, missing data and outlier analyses were performed to test the normality of the data set. As a result of these procedures, 12 data points were removed from the data set, and data analysis was initiated with 346 responses.

When the data were examined, the participants' mean Pittsburgh Sleep Quality Index (PSQI) score was 8.06 ($SD=3.46$). According to the total PSQI scores, 90 participants (26.01%) had good sleep quality, whereas 256 participants (73.99%) had poor sleep quality. The participants' mean attitude score toward healthy nutrition was 74.16 ($SD=12.10$), which falls within the high category. No participants had very low or low attitude scores. The participants' PSQI scores and ASHN are presented in Table 2.

Table 2. PSQI and ASHN total scores of the participants

PSQI Score	f	%
0	2	0.6
1	2	0.6
2	8	2.3
3	17	4.9
4	28	8.1
5	33	9.5
6	31	9.0
7	38	11.0
8	40	11.6
9	31	9.0
10	31	9.0
11	28	8.1
12	16	4.6
13	16	4.6
14	11	3.2
15	7	2.0
16	5	1.4
17	2	0.6
TOTAL	346	100.0

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Table 2. PSQI and ASHN total scores of the participants

ASHN score	f	%
Moderate	78	22.54
High	198	57.23
Ideal	70	20.23
TOTAL	346	100

Note. PSQI – Pittsburgh Sleep Quality Index; ASHN - Attitudes Towards Healthy Nutrition Scale

Because the choice of statistical test can directly affect research results (Kul, 2014), the relevant assumptions were checked before deciding which tests to use. In this context, it was examined whether the scores obtained from the tests were normally distributed, whether variances were homogeneous, and whether the scores were obtained on at least an interval-scale level.

For the evaluation of the normality assumption, distribution plots of the data as well as skewness and kurtosis coefficients were examined. Skewness and kurtosis coefficients within the range of ± 1 were taken to indicate that the data were compatible with a normal distribution. In addition, the similarity of the arithmetic mean, median, and mode values was considered supportive of normality. In all t-tests and one-way ANOVA analyses conducted in the study, Levene's test was used to evaluate the homogeneity of variances; when $p > 0.05$, the homogeneity assumption was accepted as satisfied.

Based on the results of the normality tests, Pearson correlation analysis, independent samples t-tests, and one-way analysis of variance (ANOVA) were used in the data analysis. Following one-way ANOVA, Scheffé post hoc tests were applied to determine between which groups statistically significant differences occurred.

In the statistical analyses conducted in this study, the significance level was set at $p = 0.05$. In studies examining effects, it is recommended to report effect sizes in addition to p values (American Psychological Association [APA], 2010). Accordingly, when interpreting the statistical results obtained in this study, effect size indices were considered alongside significance values.

Given the exploratory nature of this study and the large number of statistical tests, no formal correction for multiple comparisons (e.g., Bonferroni or FDR) was applied. Instead, effect sizes and patterns of association were emphasised rather than relying solely on p-values. Consequently, the risk of

Type I error is increased, and statistically significant findings, particularly those with very small effect sizes, should be interpreted with caution.

To determine the effect of the independent variable on the dependent variable, Cohen's d effect size coefficient was calculated for independent samples t-tests, and eta-squared (η^2) effect size coefficients were calculated for one-way ANOVAs. Cohen's d values below 0.20 were interpreted as very small, between 0.20 and 0.50 as small, between 0.50 and 0.80 as medium, between 0.80 and 1.00 as large, and above 1.00 as very large effects. Eta-squared values below 0.01 were interpreted as very small, between 0.01 and 0.06 as small, between 0.06 and 0.14 as medium, and above 0.14 as large effects (Büyüköztürk, 2015; Cohen, 1988).

Ethical approvals for the research

In this study, the rules specified within the scope of the "Higher Education Institutions Scientific Research and Publication Ethics Directive" were followed, and actions listed under the title of "Acts Contrary to Scientific Research and Publication Ethics" were avoided. The Istanbul Aydın University Ethics Committee granted the ethical committee approval for this study with decision number 2023/08.

Results

A weak, negative relationship was found between participants' sleep quality and their attitudes toward healthy nutrition ($r = -0.205$, $p < 0.001$; Table 3). A weak, negative relationship was also found between participants' sleep quality and EN ($r = -0.146$, $p = 0.006$), PN ($r = -0.185$, $p < 0.001$), and MP ($r = -0.156$, $p = 0.004$) sub-dimensions. However, no significant relationship was found between participants' sleep quality and IN sub-dimension ($r = -0.072$, $p = 0.182$).

Table 3. Correlations between PSQI and ASHN sub-dimensions

		ASHN	IN	EN	PN	MP
PSQI	Pearson r	-0.205*	-0.072	-0.146*	-0.185*	-0.156*
	P	<0.001	0.182	0.006	<0.001	0.004
	n	346	346	346	346	346

Note. PSQI – Pittsburgh Sleep Quality Index; ASHN - Attitudes Towards Healthy Nutrition Scale; IN - Information on Nutrition; EN - Emotion for Nutrition; PN - Positive Nutrition; MP – Malnutrition; *Correlation is significant at the $p < 0.05$ level

A weak, negative relationship was found between participants' attitudes toward healthy nutrition and the components of the sleep quality index: subjective sleep quality, sleep disturbance, use of sleep medication, and daytime dysfunction

($p < 0.05$; Table 4). However, no significant relationship was found between sleep latency, sleep duration, and habitual sleep efficiency components ($p > 0.05$).

Table 4. Correlations between ASHN scores and PSQI components

		Subjective Sleep Quality	Sleep Latency	Sleep Duration	Habitual Sleep Efficiency	Sleep Disturbance	Use of Sleep Medication	Daytime Dysfunction
	Pearson r	-0.158*	-0.087	0.063	-0.044	-0.240*	-0.224*	-0.288*
ASHN	P	0.003	0.105	0.246	0.417	<0.001	<0.001	<0.001
	n	346	346	346	346	346	346	346

Note. PSQI – Pittsburgh Sleep Quality Index; ASHN - Attitudes Towards Healthy Nutrition Scale; *Correlation is significant at the $p < 0.05$ level

According to the results of the independent samples t-test analyses (Table 5), significant differences were observed between participants' PSQI scores and their gender ($p < 0.05$), as well as between participants' ASHN scores and both their employment status and regular health check-up status ($p < 0.05$). When these findings are examined in terms of effect size, the difference in PSQI scores by gender ($d = 0.35$) indicates that gender has a small effect on sleep quality. Similarly, the difference in ASHN scores by employment status ($d = 0.33$) suggests that employment status has a small effect on attitudes

toward healthy nutrition, whereas the difference in ASHN scores according to regular health check-up status ($d = 0.47$) indicates an effect that is approaching a medium level on attitudes toward healthy nutrition.

In addition, the independent samples t-test analyses showed no significant differences between participants' PSQI scores and their education level, employment status, athlete licence status, or regular health check-up status ($p > 0.05$), nor between participants' ASHN scores and their gender, education level, or athlete licence status ($p > 0.05$).

Table 5. Independent samples t-test results for PSQI and ASHN scores by gender, education level, employment status, athlete licence status, and regular health check-ups

Scale	Variable	N	\bar{x}	sd	df	t	p	d	
PSQI ASHN	Gender	Female	231	7.66	3.192	194.73	-2.869	0.005*	-0.35
		Male	115	8.85	3.835				
	Educational Status	Female	231	74.86	12.20	344	1.520	0.129	-
		Male	115	72.77	11.83				
PSQI ASHN	Employment Status	High School and below	232	8.16	3.466	344	0.746	0.456	-
		University and above	114	7.86	3.454				
		High School and below	232	73.91	11.80	344	-0.550	0.583	-
PSQI ASHN	Employment Status	University and above	114	74.68	12.73				
		Employed	139	8.06	3.501	344	-0.001	0.999	-
		Unemployed	207	8.06	3.440				
		Employed	139	76.55	11.95	344	3.035	.003*	0.33
		Unemployed	207	72.57	11.95				

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Table 5. Independent samples t-test results for PSQI and ASHN scores by gender, education level, employment status, athlete licence status, and regular health check-ups

Scale	Variable	N	\bar{x}	sd	df	t	p	d	
PSQI	Having an Athlete's License	Yes	185	8.22	3.459	344	0.944	0.346	-
		No	161	7.87	3.461				
ASHN	License	Yes	185	75.00	12.30	344	1.378	0.169	-
		No	161	73.21	11.84				
PSQI	Regular Health Check-ups	Yes	101	7.79	3.302	344	-0.917	0.360	-
		No	245	8.17	3.523				
ASHN	Check-ups	Yes	101	78.10	13.17	194.73	3.717	<0.001*	0.47
		No	245	72.54	11.27				

Note. PSQI – Pittsburgh Sleep Quality Index; ASHN - Attitudes Towards Healthy Nutrition Scale; *Correlation is significant at the $p < 0.05$ level

According to the results of the variance analysis for independent samples (Table 6), there is a significant difference between participants' PSQI scores and their sleep patterns, smoking habits, and alcohol consumption ($p < 0.05$). When the findings are evaluated in terms of effect size, the difference in sleep pattern can be considered medium in magnitude ($\eta^2 = 0.094$), while the differences in smoking ($\eta^2 = 0.048$) and alcohol consumption ($\eta^2 = 0.020$) can be considered small. No significant difference was found between their physical activity levels and the presence of hereditary diseases in their families ($p > 0.05$).

As a result of the post-hoc Scheffe test performed to determine the difference between the groups, differences ($p < 0.05$) were found that the differences come from between individuals who sleep regularly and those who sleep irregularly or those who sometimes sleep regularly and sometimes irregularly, between individuals who never smoke and those who smoke more than ten cigarettes a day, and between individuals who used to smoke but no longer do and those who smoke ten or more cigarettes a day, between individuals who never consume alcohol and those who consume alcohol a few times a month.

According to the results of the variance analysis for in-

dependent samples, there is a significant difference between participants' ASHN scores and their daily physical activity, sleep patterns, and smoking habits ($p < 0.05$). When the findings are evaluated in terms of effect size, the difference related to daily physical activity can be considered to have a medium effect ($\eta^2 = 0.108$), whereas the difference related to sleep pattern shows a small effect ($\eta^2 = 0.037$), and the difference related to smoking indicates a small and limited effect ($\eta^2 = 0.036$). No significant difference was found regarding the presence of hereditary diseases in the family and alcohol consumption ($p > 0.05$).

As a result of the post-hoc Scheffe test performed to determine the difference between the groups, differences ($p < 0.05$) were found between those who never do physical activity and those who do physical activity three to four days a week, five to six days a week, and every day, and between those who do physical activity one to two days a week and those who do physical activity three to four days and five to six days a week, individuals who sleep regularly and those who sleep irregularly, as well as between those who sleep irregularly and those who sometimes sleep regularly and irregularly, those who smoked for a period and no longer smoked, and those who smoked ten cigarettes or more a day.

Table 6. ANOVA results for participants' PSQI scores and ASHN scores based on daily physical activity, sleep patterns, presence of hereditary diseases in the family, smoking, and alcohol consumption

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Table 6. ANOVA results for participants' PSQI scores and ASHN scores based on daily physical activity, sleep patterns, presence of hereditary diseases in the family, smoking, and alcohol consumption

Scale	Variable	N	\bar{x}	sd		Sum of Squares	df	Mean Square	F	Sig.	η^2	Significant Differences Between Groups (Scheffe)
PSQI	None	36	8.83	3.427	Between Groups	48.485	4	12.121	1.203	0.401	-	
	1-2 times a week	83	8.34	3.542	Within Groups	4080.359	341	11.966				
	3-4 times a week	147	7.79	3.401	Total	4128.844	345					
	5-6 times a week	59	8.10	2.998								
	Every day	21	7.38	4.642								
	Total	346	8.06	3.459								
ASHN	None	36	65.89	9.322	Between Groups	5462.269	4	1365.567	10.330	0.000*	0.108	
	1-2 times a week	83	70.71	10.909	Within Groups	45079.341	341	132.197				
	3-4 times a week	147	75.76	10.891	Total	50541.610	345					1-3, 4, 5 2-3, 4, 5
	5-6 times a week	59	77.86	13.136								
	Every day	21	80.43	15.734								
	Total	346	74.16	12.104								
PSQI	Regular	80	6.44	2.950	Between Groups	386.199	2	193.099	17.697	<0.001*	0.094	
	Irregular	111	9.32	3.570	Within Groups	3742.645	343	10.912				1-2, 3 2-3
	Sometimes Regular, Sometimes Irregular	155	7.99	3.276	Total	4128.844	345					
	Total	346	8.06	3.459								
ASHN	Regular	80	75.84	14.161	Between Groups	1878.734	2	939.367	6.621	0.002*	0.037	
	Irregular	111	70.77	10.621	Within Groups	48662.876	343	141.874				1-2 2-3
	Sometimes Regular, Sometimes Irregular	155	75.73	11.512	Total	50541.610	345					
	Total	346	74.16	12.104								
PSQI	Yes	59	8.58	3.292	Between Groups	21.267	2	10.633	0.888	0.412	-	
	No	236	7.91	3.516	Within Groups	4107.577	343	11.975				
	Not Sure	51	8.14	3.388	Total	4128.844	345					
	Total	346	8.06	3.459								
ASHN	Yes	59	75.88	11.987	Between Groups	217.677	2	108.839	0.742	0.477	-	
	No	236	73.89	12.285	Within Groups	50323.933	343	146.717				
	Not Sure	51	73.45	11.420	Total	50541.610	345					
	Total	346	74.16	12.104								
PSQI	Never Smoked	169	7.56	3.357	Between Groups	196.897	3	65.632	5.709	<0.001*	0.048	
	Used to Smoke, but Quit	49	7.31	3.362	Within Groups	3931.947	342	11.497				
	10 or more cigarettes a day	55	8.62	3.291	Total	4128.844	345					1-4 2-4
	Less than 10 cigarettes a day	73	9.29	3.557								
	Total	346	8.06	3.459								
ASHN	Never Smoked	169	75.27	12.597	Between Groups	1830.939	3	610.313	4.285	0.005*	0.036	
	Used to Smoke, but Quit	49	77.67	11.689	Within Groups	48710.671	342	142.429				
	Less than 10 cigarettes a day	55	71.73	12.178	Total	50541.610	345					2-4
	10 or more cigarettes a day	73	71.08	10.195								
	Total	346	74.16	12.104								

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Table 6. ANOVA results for participants' PSQI scores and ASHN scores based on daily physical activity, sleep patterns, presence of hereditary diseases in the family, smoking, and alcohol consumption

Scale	Variable	N	\bar{x}	sd		Sum of Squares	df	Mean Square	F	Sig.	η^2	Significant Differences Between Groups (Scheffe)
PSQI	Never Consumed	155	7.53	3.425	Between Groups	81.627	2	40.813	3.459	0.033*	0.020	
	A few times a month	163	8.54	3.393	Within Groups	4047.217	343	11.799				1-2
	A few times a week	28	8.18	3.732	Total	4128.844	345					
	Total	346	8.06	3.459								
ASHN	Never Consumed	155	73.81	12.500	Between Groups	378.327	2	189.164	1.293	0.276		
	A few times a month	163	75.01	11.490	Within Groups	50163.282	343	146.249				
	A few times a week	28	71.21	13.212	Total	50541.610	345					
	Total	346	74.16	12.104								

Note. PSQI – Pittsburgh Sleep Quality Index; ASHN - Attitudes Towards Healthy Nutrition Scale; N – number of participants; \bar{x} = mean; sd – standard deviation; df – degrees of freedom; F – F-test value; Sig. – significance level (p-value); η^2 – eta squared (effect size); *Indicates significance at the $p < 0.05$ level.

Discussion

The current study explored the relationship between individuals' sleep quality and attitudes toward healthy eating, revealing several significant but weak correlations. These findings align with previous research identifying a connection between sleep patterns and various health behaviours, including dietary choices and physical activity. This discussion section provides a detailed interpretation of the results, considers the implications of the findings, and suggests potential directions for future research.

The study found a weak negative correlation between sleep quality and healthy eating attitudes ($r = -0.205$, $p < 0.05$). Although the strength of this relationship is small, it is consistent with existing literature, which suggests that poor sleep can lead to impaired cognitive functioning and emotional regulation, thereby influencing dietary behaviours. Poor sleep quality has been associated with increased cravings for high-calorie foods and decreased motivation for maintaining healthy eating habits (Akhlaghi & Kohanmoo, 2023; Yang & Tucker, 2021). The findings of this study support these assertions, as individuals with lower sleep quality reported less favourable attitudes toward healthy eating. However, it is essential to note that the variance explained by sleep quality about healthy eating attitudes was small, suggesting that while sleep quality plays a role, other factors are likely more influential in shaping dietary attitudes. It is important to stress that the observed associations were small in magnitude, explaining approximately 4% of the variance in attitudes toward healthy nutrition. From a public-health perspective, sleep quality is only one minor factor among many that contribute to how individuals feel and think about healthy eating. Improving sleep alone is therefore unlikely to produce large changes in dietary attitudes or behaviour. However, it may form one modest element within broader, multi-component interventions that also target diet, physical activity, stress management, and the wider social environment. Stress, emotional well-being, socio-economic sta-

tus, and access to healthy foods may also significantly affect attitudes toward nutrition (Cardoso et al., 2020; Nagy-Pénczes, Vincze, & Bíró, 2020). Future studies should consider a broader range of factors to capture a more comprehensive understanding of what influences dietary attitudes.

A more granular analysis of the relationship between sleep quality and the sub-dimensions of healthy eating attitudes revealed several interesting patterns. Significant negative correlations were found for the EN, PN, and MP sub-dimensions, but not for IN. This finding suggests that poor sleep quality may significantly impact individuals' emotional and behavioural relationships with food rather than their cognitive understanding of nutrition. In other words, individuals who experience poor sleep might know what constitutes a healthy diet but struggle to implement this knowledge due to emotional and behavioural barriers, such as stress or mood swings associated with lack of sleep (O'Connor et al., 2022; Yeo et al., 2024). This finding adds an important dimension to the existing body of literature, as it suggests that sleep interventions targeting emotional regulation may improve sleep quality and individuals' ability to make healthier food choices. Emotional eating and stress-induced food consumption are well-documented phenomena, and the connection between sleep and these behaviours warrants further exploration (Pensgaard et al., 2023; Wiss, Avena, & Gold, 2020).

When the individual components of sleep quality (e.g., subjective sleep quality, sleep disturbances, daytime dysfunction) were examined, the results showed that daytime dysfunction had the strongest negative correlation with attitudes toward healthy eating ($r = -0.288$, $p < 0.05$). This finding is particularly noteworthy as it suggests that the impact of poor sleep on daytime functioning (e.g., fatigue, difficulty concentrating) may be a key factor in explaining the connection between sleep and unhealthy eating patterns (Chaput et al., 2022; Gomes et al., 2023). This aligns with the notion that poor daytime functioning due to sleep deprivation can lead to lower energy levels, reduced self-control, and a reliance

on convenience foods, which are often less healthy (Gooderham, 2024; Stover et al., 2023). Improvements in sleep quality, particularly through daytime dysfunction reduction, would boost individuals' capability to maintain healthier eating patterns (Amato et al., 2024; Bovenzi et al., 2024).

The study found that gender was a significant predictor of sleep quality, with men reporting worse sleep quality than women. Biological, psychological, and lifestyle factors may explain this gender difference. For instance, hormonal fluctuations, stress, and differences in sleep hygiene practices may contribute to gender disparities in sleep quality (Andersen et al., 2023; Curtis et al., 2024; Rodríguez-Aragón et al., 2024). However, no significant differences in sleep quality were observed based on education level, employment status, or athletic licensing. These findings suggest that these socio-demographic factors do not strongly influence sleep quality in this sample.

One of the study's most significant findings was the role of lifestyle factors—namely physical activity, smoking, and alcohol consumption—in sleep quality and healthy eating attitudes. Regular physical activity was associated with better sleep quality and more positive attitudes toward healthy eating, which is consistent with the extensive literature on the benefits of exercise for both physical and mental health (Mantzorou et al., 2023; Rassolnia & Nobari, 2024; Trajković et al., 2023). The pattern in which attitudes toward healthy nutrition form part of a wider lifestyle profile aligns with previous findings showing that these attitudes are associated with exercise addiction among physically active individuals (Orhan et al., 2024). This finding underscores the importance of promoting physical activity to improve overall health behaviours, including sleep and nutrition. Similarly, smoking and alcohol consumption were negatively correlated with sleep quality and healthy eating attitudes. This is consistent with previous research that links smoking and excessive alcohol consumption with poorer sleep and unhealthier dietary patterns (Doak et al., 2023; Faris et al., 2023). The fact that these lifestyle factors were significant predictors highlights the need for public health interventions targeting smoking cessation, alcohol moderation, and increased physical activity to improve sleep quality and dietary habits (Chai et al., 2024; Mace et al., 2024).

The findings of this study have several practical implications for public health interventions. Given the interconnectedness of sleep quality, physical activity, and dietary behaviours, interventions aimed at improving one aspect of health (e.g., sleep hygiene) could have spillover effects on other behaviours, such as healthier eating and increased physical activity (Chevance et al., 2022; Ranby et al., 2023). For instance, sleep education programs that teach individuals how to improve their sleep quality could also incorporate stress management and emotional regulation lessons, enhancing individuals' ability to maintain healthy eating habits (Irish et al., 2015; Leonidis et al., 2021). Additionally, the findings suggest that interventions should be tailored to address emotional and behavioural aspects of eating rather than focusing solely on cognitive knowledge. The combination of low sleep quality and impaired emotional management usually prevents people from sticking to their healthy eating plans despite knowing the health advantages (Benjamins et al., 2021; Brytek-Matera, 2021).

Despite its valuable contributions, this study has several limitations. Although the sample size was adequate for statistical analysis, it may not represent the broader population, which limits the generalizability of the findings. All variables were assessed through self-report questionnaires, which are subject to recall bias, social desirability effects, and inaccuracies in self-perception (e.g., of sleep quality or health attitudes); objective measures of sleep (such as actigraphy) and more detailed dietary assessments (such as food diaries or 24-hour recalls) would allow stronger inferences in future research. A further conceptual limitation is that the ASHN assesses attitudes toward healthy nutrition rather than actual dietary intake or objectively observed eating behaviour; the findings therefore pertain to how participants think and feel about healthy eating, not to what they actually eat in daily life. Attitudes and behaviours are related but not identical, and future research should combine attitudinal measures with detailed dietary assessments to clarify how sleep quality is linked to concrete eating patterns. Multivariable adjusted analyses controlling for potential confounders such as socioeconomic status, chronic health conditions, perceived stress, or use of sleep medication were not conducted. Some relevant variables were either not measured or were not available in sufficient detail, and the study was designed primarily as an exploratory analysis of bivariate relationships. As a result, the observed associations between sleep quality and attitudes toward healthy nutrition may be partially or wholly explained by unmeasured confounding factors; future studies should incorporate richer information on sociodemographic, clinical, and psychosocial characteristics and use multivariable models to obtain more robust estimates. Another area for future research is the exploration of variables that may mediate or moderate the relationship between sleep and dietary attitudes, such as psychological well-being, stress levels, or access to healthy food options, and longitudinal studies that track changes in sleep and dietary behaviours over time would provide greater insight into the causal direction of these relationships.

Conclusions

In conclusion, this study highlights the intricate relationship between sleep quality and attitudes toward healthy eating, with lifestyle factors such as physical activity, smoking, and alcohol consumption playing key roles. While the correlations observed in this study were weak, the findings underscore the importance of addressing sleep quality as part of holistic health interventions to improve dietary behaviours. Future research should continue to explore the underlying mechanisms linking sleep and diet, emphasizing emotional regulation and lifestyle modifications.

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Conflict of Interest

The authors report no conflict of interest.

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15-Second Repeated Vertical Jump Models versus Ergometer Approaches for Lower-Limb Average Power Assessment: A Preliminary Exploratory Comparison

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Abstract

Lower-limb average power is an important indicator of neuromuscular performance and can be assessed either indirectly through computational models derived from repetitive vertical jumps or directly using ergometers that quantify mechanical output. However, these approaches often yield different values, complicating interpretation and comparison across studies. This preliminary, exploratory within-subject study ($n=5$) aimed to examine discrepancies between lower-limb average power estimated from computational models applied to 15-second vertical jump tests and that measured during short-duration maximal efforts on cycle- and row-ergometers. Five male sport science university students performed a 15-second repeated vertical jump test assessed using the OptoJump Next system (Microgate, Bolzano, Italy). Average power was calculated using the Bosco, Miron Georgescu (MG), and Miron Georgescu Modified 15-second (MGM-15) formulas. Each participant subsequently completed two 20-second all-out trials on the Concept2 BikeErg and RowErg (Concept2 Inc., Morrisville, Vermont, USA). The analysis revealed a significant main effect of method ($F(1.03, 4.12)=77.04$, $p=0.001$, $\eta^2=0.95$). The Bosco and MG equations generated substantially higher power outputs compared with both ergometer assessments ($p<0.05$). The MGM-15 model produced estimates not statistically different from RowErg ($p>0.05$), while slightly lower than those recorded on BikeErg ($p<0.01$). Substantial discrepancies were observed in lower-limb average power values obtained from different computational models applied to repeated vertical jump data. While classical equations produced markedly higher estimates, the MGM-15 formulation yielded power values that were closer to those obtained from direct ergometer measurements, highlighting the influence of computational assumptions on jump-derived power estimates.

Keywords: lower-limb power, ergometer, vertical jump, computational modelling, athlete performance assessment

Introduction

Lower-limb power is a fundamental determinant of athletic performance, reflecting neuromuscular system's ability to generate high mechanical output within short time intervals (Acar et al., 2025; Gross & Lüthy, 2020; Pleša et al., 2025). Accurate assessment of this parameter provides critical insights into mechanical efficiency, fatigue resistance, and sport-spe-

cific adaptations (Ding et al., 2025; Ivanov, 2025; Khemiri et al., 2025). Among various performance indicators, average power output is widely employed to characterize both the mechanical and metabolic dimensions of lower-limb function (DeLeo et al., 2025; Lai et al., 2025). In laboratory and field settings, power output can be quantified either indirectly, through computational models applied to vertical jump data

(Geantă & de Hillerin, 2023; Geantă & de Hillerin, 2025), or directly, using ergometric devices that record mechanical work in real time (DeLeo et al., 2025; Kostka & Kostka, 2024).

Building on this interest, early studies employed repeated-jump protocols, such as the 15-s repeated vertical jump test, to investigate muscular performance (Geantă et al., 2025). Miron Georgescu's (1953) pioneering model proposed one of the first theoretical formulations relating flight and contact times to average power output. His original protocol consisted of 35 continuous jumps, traditionally described as "ball-like jumps," from which the first 30 valid repetitions were analyzed (Geantă et al., 2025). In subsequent decades, Bosco, Luhtanen and Komi (1983) introduced a simplified biomechanical approach based solely on flight time, which became widely adopted in sports diagnostics. Extending these foundational approaches, Pierre de Hillerin (1997) developed the Modified Miron Georgescu Method (MGM-15), designed to capture not only mechanical outputs but also factors related to motor control and fatigue regulation. This approach aligns with the psycho-neuro-motor framework, integrating psychological, neural, and motor components to provide a more comprehensive representation of muscular effort and its temporal dynamics (Marin et al., 2015).

Recent computational studies employing modern photocell-based technologies such as OptoJump have revisited these classical models and revealed substantial discrepancies in average power values derived from identical jump data (Geantă & de Hillerin, 2025; Geantă et al., 2025). In particular, conventional equations, including those proposed by Georgescu (1953) and Bosco et al. (1983), have been shown to systematically overestimate average power compared with more recent models. Despite these methodological advances, direct comparisons between jump-based computational models and ergometer-derived mechanical power measurements remain scarce. This gap may lead to inconsistencies in performance evaluation and training prescription, underscoring the need for approaches that integrate indirect jump-based estimates with direct, real-time mechanical measurements (Borges et al., 2025; Joshi & Singh, 2024; Khemiri et al., 2025; Wehbe et al., 2015).

Modern ergometers, such as the Concept2 BikeErg and RowErg (Concept2, n.d.), provide real-time measurements of mechanical power under standardized resistance and cadence conditions and have been widely employed in high-intensity protocols involving trained athletes (Treff et al., 2022; Tongwu et al., 2025; Turner & Rice, 2021). Studies evaluating these devices have reported acceptable-to-high levels of technical accuracy and reliability in both cycling and rowing protocols (Podstawski et al., 2025; Treff et al., 2022). Furthermore, both ergometer modalities effectively engage the major lower-limb extensors, providing a relevant mechanical reference for comparative analysis (Czajkowska et al., 2023; Driss & Vandewalle, 2013; Gavala-González et al., 2024), and produce repeatable power measurements across different populations and exercise contexts (García-Ramos et al., 2018; Pérez-Castilla & García-Ramos, 2021; Wehbe et al., 2015).

To date, no study has directly compared multiple computational models of jump-derived average power with direct mechanical power measurements obtained from ergometers. Bosco et al. (1983) were among the first to explore the relation-

ship between jump-based estimations and laboratory-derived anaerobic performance by comparing a continuous jump test with a modified Wingate protocol; however, that comparison relied on indirect estimations and analog instrumentation, which may have limited precision and external validity.

Therefore, the present preliminary and exploratory study extends the research line initiated by Geantă and de Hillerin (2025), representing the first systematic attempt to evaluate and contrast three computational models of lower-limb average power estimation against real-time, directly measured mechanical power recorded during short-duration maximal efforts. Based on previous findings, it was hypothesized that the MGM-15 model would yield average power values more closely aligned with the physiological reality reflected by direct ergometer measurements.

Accordingly, this study aimed to examine which computational approach yields average power estimates that tend to align more closely with direct mechanical output obtained from ergometer measurements.

Materials and methods

Participants

Five physically active male university students (age: 20.2 ± 0.45 years; height: 178.6 ± 4.72 cm; body mass: 73.0 ± 8.12 kg) from the Faculty of Physical Education and Sport volunteered for this preliminary study. All were recreationally trained, with no musculoskeletal injuries or medical conditions affecting lower-limb neuromuscular performance. Before data collection, participants took part in a familiarization session in which they practiced both jump and ergometer protocols to ensure consistent execution and to minimize learning-related variability (Walsh et al., 2022; Wehbe et al., 2015). All subjects were informed about the study's procedure and risk before signing written consent forms. The study was approved by the Ethics Committee of the Aurel Vlaicu University of Arad (Registration number: 210/16.04.2025) adhering to the ethical principles of the Declaration of Helsinki.

Research design

The present preliminary study followed a cross-sectional within-subject design, allowing each participant to serve as their own control. The objective was to compare the average mechanical power output obtained from three computational models (Bosco, MG, MGM-15) with direct mechanical measurements recorded during maximal short-duration efforts on two ergometers (Concept2 BikeErg and Concept2 RowErg; Concept2 Inc., Morrisville, Vermont, USA). Each participant performed one 15-second repeated-jump test (15s-Jumps) using the Microgate OptoJump Next photocell system (Microgate, Bolzano, Italy), followed by two 20-second maximal effort ergometer tests. To control for fatigue, ergometer test order (BikeErg vs RowErg) was counterbalanced across participants. A 10-minute passive recovery period separated the jump and the first ergometer test, while a 15-minute passive rest interval was maintained between the two ergometers efforts, consistent with recovery protocols validated in short-duration power testing (Driss & Vandewalle, 2013; Maté-Muñoz et al., 2022; Turner & Rice, 2021).

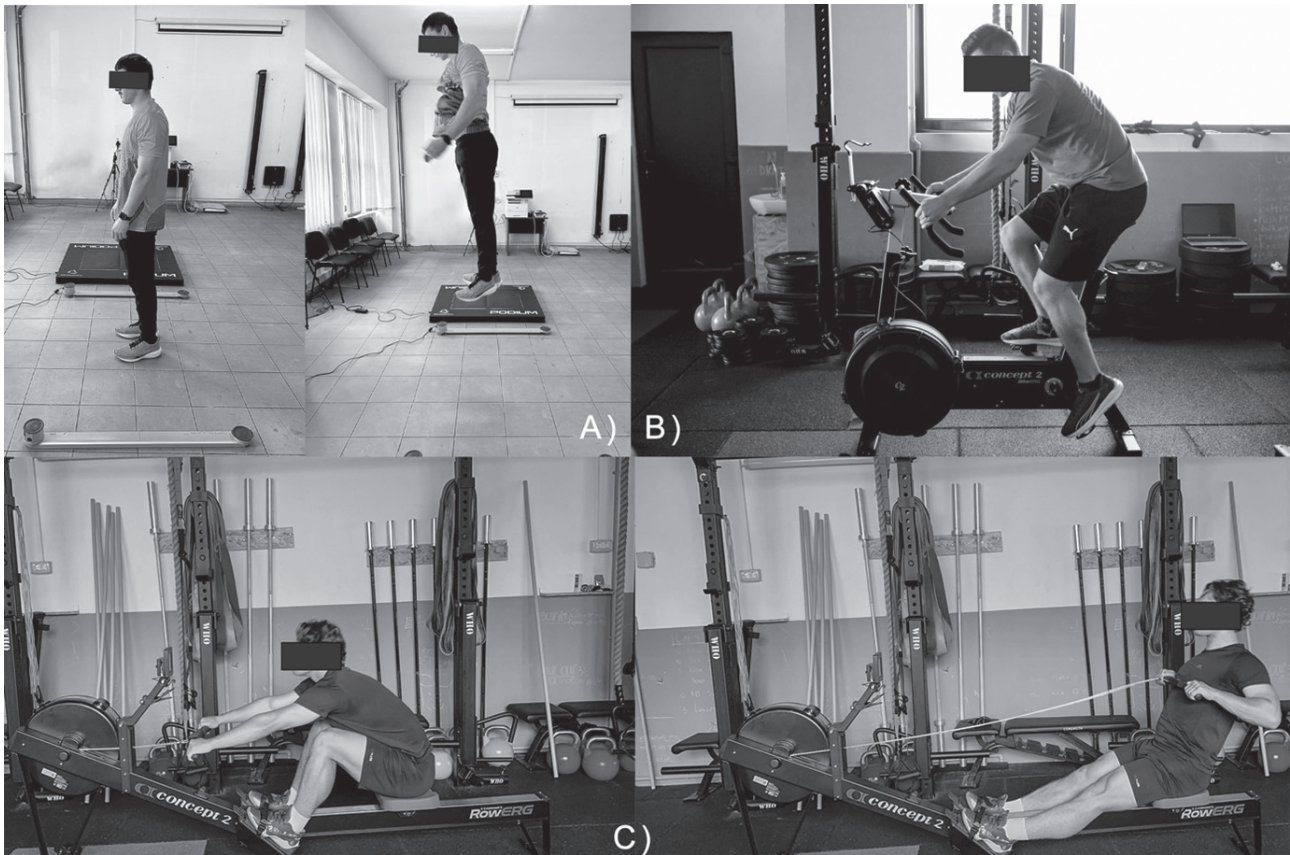


Figure 1. Assessment protocols of the study: (A) 15-s jumping test; (B) BikeErg test; (C) RowErg test.

Experimental procedure

Vertical jump test

Participants completed a single 15-second series of repetitive vertical jumps with arm swings and maximal intensity, minimizing ground contact time (T_c) and maximizing flight time (T_f). The OptoJump Next system recorded contact and flight times with a sampling resolution of 0.001s (Microgate, n.d.). All measurements were conducted in the same research center and environmental conditions. The raw data were exported in XML format and subsequently processed in Excel for the computation of average mechanical power based on three established mathematical models.

Average power calculation formulas for 15s jumps

Average power output (PU, in $W \cdot kg^{-1}$ or W/kg) was computed using the equations previously exposed by Geantă et al. (2025), corresponding to the MG (Georgescu, 1953), Bosco (Bosco et al., 1983), and MGM-15 (Hillierin, 1997) methodologies:

$$\text{MG model:} \quad PU = 1.5 \times \frac{g^2 \times T_f^2}{8 \times T_c} \quad (1)$$

$$\text{Bosco model:} \quad PU = 2 \times \frac{g^2 \times T_f \times 15}{4n \times (15 - T_f)} \quad (2)$$

$$\text{MGM-15 model:} \quad PU = \frac{g^2 \times T_f^2}{8 \times (T_c + T_f)} \quad (3)$$

where:

PU = Average power output (W/kg)

m = Body mass (kg)

g = Gravitational acceleration (typically 9.81 m/s²),

n = Number of jumps

t = Total test time (15 seconds)

T_f = Flight time (s)

T_c = Contact time (s)

Worked example

A worked example is provided for both the Miron Georgescu (MG) and Modified Miron Georgescu–15 s (MGM-15) models using raw temporal output from the OptoJump Next system. Flight time (T_f), contact time (T_c), and jump height (h, derived from flight time) were used to illustrate the calculations.

The computational procedure for the MGM-15 model was described previously (Geantă et al., 2025); here, the same approach is applied to independent jump data and extended to include the MG model for comparative purposes. Bosco average power output was obtained directly from the OptoJump software and did not require offline computation.

For a representative jump, the parameters were $T_c=0.211$ s, $T_f=0.570$ s, corresponding to a jump height of 0.398 m (39.8 cm). Substituting into the MG equation (1):

$$PU = 1.5 \times \frac{g^2 \times T_f^2}{8 \times T_c} = 1.5 \times \frac{(9.81)^2 \times (0.570)^2}{8 \times 0.211} = 1.5 \times \frac{96.2361 \times 0.3249}{1.688} = 27.75 \text{ W/kg} \quad (4)$$

Using the same jump in the MGM-15 equation (3), which accounts for both flight and contact time:

$$PU = \frac{g^2 \times T_f^2}{8 \times (T_c + T_f)} = \frac{(9.81)^2 \times (0.570)^2}{8 \times (0.211 + 0.570)} = \frac{96.2361 \times 0.3249}{6.248} = 4.99 \text{ W/kg} \quad (5)$$

The calculations were then applied to a subsequent jump with $T_c=0.185$ s, $T_f=0.508$ s, and a jump height 0.316 m (31 cm), resulting in $MG=25.16$ W/kg and $MGM-15=4.48$ W/kg. This same approach was repeated for all jumps recorded during the 15-second test series, and the final values for each participant were determined as the arithmetic mean of all individual MG and MGM-15 power outputs. All computations can be reproduced directly from the raw OptoJump XML export, which contains the complete set of temporal and kinematic parameters. This worked example is intended for illustration; the procedure was applied consistently to every jump in the series to derive the final MG and MGM-15 results reported in this study.

Ergometer test

Each participant performed two maximal-effort trials, one on the Concept2 BikeErg and one on the Concept2 RowErg, both equipped with PM5 performance monitors (Concept2 Inc., Vermont, USA).

Before testing, participants completed a dedicated familiarization session on each ergometer to establish proper technique and consistent mechanical output.

During testing, participants were instructed to accelerate as quickly as possible and sustain maximal effort for 20 seconds. This duration corresponds to the minimum standardized test length provided by the Concept2 PM5 monitor for maximal effort assessments, and was therefore used consistently across participants (Concept2, n.d.). Seat position, handlebar height, and resistance settings were individually adjusted during familiarization and kept constant across all tests. Mean power output for the 20-second maximal effort, as reported by the Concept2 PM5 monitor, was used for analysis and normalized to body mass. A 15-minute rest period was provided between BikeErg and RowErg efforts to ensure adequate recovery and to minimize the influence of fatigue on subsequent performance, consistent with previous recommen-

dations for high-intensity testing (Maté-Muñoz et al., 2022).

Statistical analysis

All data were analyzed using SPSS v31 (IBM Corp., Armonk, NY, USA), and graphical representations were produced in GraphPad Prism v10.3 (GraphPad Software, San Diego, CA, USA). Descriptive statistics (mean±SD) were calculated for each condition. Data normality was verified using the Shapiro–Wilk test. Differences among the five testing conditions (Bosco, MG, MGM-15, BikeErg, RowErg) were assessed via a one-way repeated-measures ANOVA. When the assumption of sphericity was violated according to Mauchly's test ($p<0.05$), the Greenhouse–Geisser correction was applied ($\epsilon=0.26$). Post-hoc pairwise comparisons were performed using Bonferroni-adjusted tests, with statistical significance set at $p<0.05$. Effect sizes were reported as partial eta squared (η^2) and interpreted according to Cohen (2013), where values of $\eta^2 \geq 0.01$, ≥ 0.06 , and ≥ 0.14 correspond to small, medium, and large effects, respectively. Given the very small sample size ($n=5$), inferential statistics were used cautiously and exclusively to explore systematic within-subject differences rather than to support population-level inference or model validation. Accordingly, effect sizes and descriptive trends were emphasized alongside p-values, consistent with recommendations for exploratory and preliminary research designs.

Results

Descriptive statistics for all testing methods are shown in Table 1 and Figure 2. Mean values indicate substantial variability across the five power assessment approaches. The Bosco model produced the highest mean power (39.42 ± 7.73 W/kg), followed by the MG model (20.38 ± 5.59 W/kg). In contrast, the MGM-15 model yielded much lower values (4.13 ± 0.53 W/kg), closer to the directly measured values from the BikeErg (8.67 ± 0.39 W/kg) and RowErg (5.43 ± 0.75 W/kg) tests.

Table 1. Descriptive statistics (Mean ± SD) of average power (W/kg) across assessment methods

Variable	Average Power (W/kg)	
	Mean	SD
Bosco	39.42	7.73
MG	20.38	5.59
MGM-15	4.13	0.53
BikeErg	8.67	0.39
RowErg	5.43	0.75

Note. Data are presented as mean ± SD. Bosco, MG, and MGM-15 are calculated power models, whereas BikeErg and RowErg are based on directly measured power output.

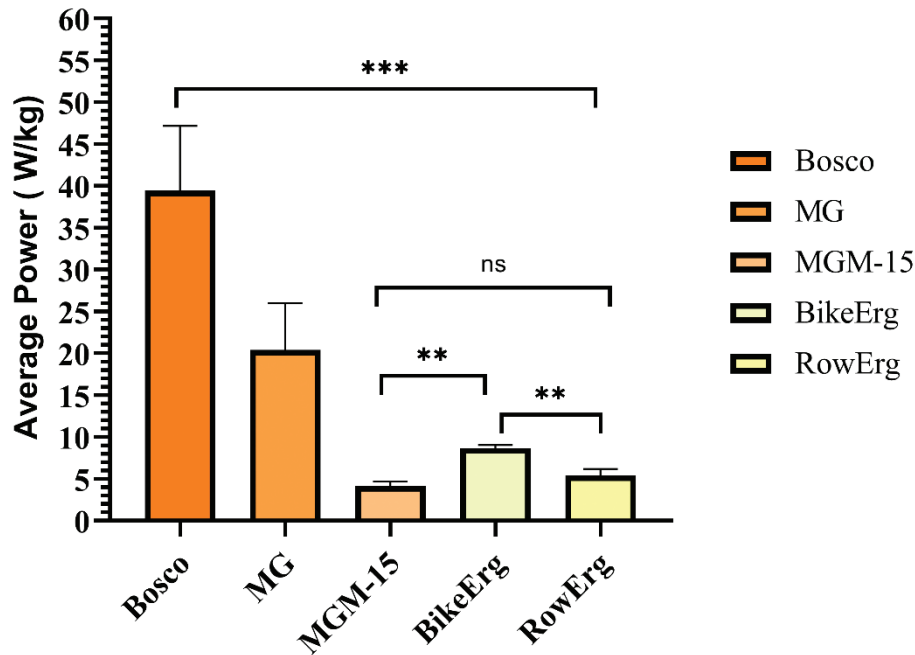


Figure 2. Descriptive statistics (Mean \pm SD, W/kg) and results of inferential Bonferroni-adjusted pairwise comparisons across computational models (Bosco, MG, MGM-15) and direct ergometer measurements (BikeErg, RowErg)

Note. Symbols indicate statistically significant differences (** $p < 0.01$, *** $p < 0.001$, $p < 0.05$, ns = not significant).

A one-way repeated-measures ANOVA confirmed a significant main effect of method on power output ($F(1.03, 4.12) = 77.04$, $p = 0.001$, $\eta^2 = 0.95$), indicating that power estimates differed systematically between models (Table 2). Mauchly's test revealed a violation of sphericity ($\chi^2(9) = 38.35$,

$p < 0.001$); therefore, the Greenhouse–Geisser correction was applied. The large effect size ($\eta^2 = 0.95$) indicates substantial differences in methodology between the approaches. This finding is particularly important in this exploratory study, which used a small sample.

Table 2. Repeated-measures ANOVA results for average power output across computational and direct measurement methods

Source	SS	df	MS	F	p	η^2
Method	4367	1.03, 4.12	1092	77.04	0.001	0.95
Error	226.7	16	14.17	-	-	-

Note. Greenhouse–Geisser correction ($\epsilon = 0.26$) applied due to violation of sphericity (Mauchly's $W = 0.073$, $p < 0.05$). The main effect of method was significant ($p = 0.001$, $\eta^2 = 0.95$), indicating strong differences between models

Post-hoc Bonferroni comparisons (Figure 2 and Table 3) revealed that both Bosco and MG models significantly overestimated average power relative to all other conditions ($p < 0.05$). The MGM-15 model produced values that were not signifi-

cantly different from RowErg outputs ($p = 0.36$) but were slightly lower than BikeErg results ($p = 0.003$). BikeErg and RowErg differed significantly ($p = 0.004$).

Table 3. Bonferroni-Adjusted Pairwise Comparisons

Comparison	Mean Difference (W/kg)	95% CI of Diff	p
Bosco vs MG	19.04	[13.11–24.98]	0.001
Bosco vs MGM-15	35.29	[17.21–53.37]	0.004
Bosco vs BikeErg	30.75	[10.47–51.03]	0.011
Bosco vs RowErg	34.00	[14.21–53.79]	0.007
MG vs MGM-15	16.25	[3.44–29.05]	0.021

(continued from previous page)

Table 3. Bonferroni-Adjusted Pairwise Comparisons

Comparison	Mean Difference (W/kg)	95% CI of Diff	p
MG vs BikeErg	11.71	[-3.20–26.62]	0.117
MG vs RowErg	14.95	[0.40–29.50]	0.045
MGM-15 vs BikeErg	-4.54	[-6.79–2.29]	0.004
MGM-15 vs RowErg	-1.29	[-3.63–1.04]	0.363
BikeErg vs RowErg	3.25	[1.61–4.89]	0.004

Note. Bonferroni correction was applied for multiple comparisons ($\alpha=0.05$). Significant pairwise differences are shown in bold ($p<0.05$). The MGM-15 model differed significantly from BikeErg ($p=0.004$) but not from RowErg ($p=0.36$)

Discussion

This study aimed to provide a preliminary, exploratory comparison of average power estimates derived from classical jump-based computational models and direct mechanical outputs recorded during short-duration maximal efforts on ergometers. Statistical analysis with Bonferroni-adjusted post-hoc comparisons revealed a significant main effect of method ($F(1.03, 4.12)=77.04, p=0.001, \eta^2=0.95$), indicating that the different approaches produced systematically divergent power values. This large effect highlights that methodological choice is a major determinant of measured performance outcomes in lower-limb power assessment.

Comparison of computational models

Among the investigated methodologies, both the Bosco and MG models yielded considerably greater average power values when contrasted with the direct ergometer data. This observation aligns with prior research indicating that equations derived from jump performance frequently overestimate muscular output when compared to direct mechanical assessments, such as the Wingate test (Bosco et al., 1983; Driss & Vandewalle, 2013). The Bosco et al. (1983) model assumes constant mechanical efficiency and uniform jump mechanics across repetitions, disregarding the progressive reduction in force and stretch-shortening cycle efficiency typically observed during repeated jumps. This simplification may lead to an overestimation of mean power output (Acar et al., 2025; Khemiri et al., 2025). Similarly, the MG model relies on a theoretical derivation of the relationship between potential and kinetic energy, which does not account for real-time fluctuations in contact and flight durations.

Consequently, these models present a simplified biomechanical representation that deviates from the actual patterns of energy transfer observed during sustained neuromuscular effort. The observed discrepancy suggests that while these models offer practical field assessment tools, their outputs might not precisely reflect the intricate interplay of concentric and eccentric muscle actions and metabolic contributions inherent in dynamic movements (Samozino et al., 2008)

MGM-15 vs. direct ergometer measurements

In contrast, the MGM-15 model demonstrated the closest alignment with direct ergometer outputs. Although its

values were slightly lower than those recorded on the BikeErg ($p<0.01$), they did not differ significantly from the RowErg results ($p>0.05$). This close similarity can be attributed to the model's careful accounting of both flight and contact time (Hillierin, 1997). These parameters are vital, as they comprehensively represent the dynamic and physiologically relevant alternation between concentric propulsion and eccentric phases inherent in repetitive jumping actions (Geantă & de Hillierin, 2025). Incorporating flight time into the formula enables the MGM-15 model to capture the full physiological structure of repeated jumping, encompassing both the eccentric-concentric transition and the airborne phase characteristic of cyclic, rebound-type (ballistic) movements. By integrating these distinct temporal components, the model may more accurately account for subtle fluctuations in mechanical efficiency intrinsic to genuine cyclic power production (Geantă et al., 2025), offering a plausible methodological explanation for why its estimated power values tended to be closer to those obtained from direct ergometer measurements. Ergometers, by their nature, continuously and precisely register the actual mechanical work performed, offering a robust standard for dynamic, real-time power output across the same muscle groups involved in jumping (Lai et al., 2021; Turner & Rice, 2021).

Discrepancies with ergometer-based outputs

The pronounced difference between the Bosco model and ergometer values echoes Bosco's own observations when comparing his jump test to the Wingate cycle test more than four decades ago (Bosco et al., 1983). The present findings reaffirm that such discrepancies persist even with modern measurement technologies. While ergometers directly measure the total mechanical work performed against external resistance (Pitto et al., 2025), jump-based models infer power indirectly from kinematic parameters, which are sensitive to small errors in timing or execution (Rong et al., 2025). This fundamental difference in measurement principles likely explains the magnitude of the observed discrepancies, particularly in short-duration maximal tasks, where instantaneous output fluctuates rapidly (Gross & Lüthy, 2020; Pérez-Castilla & García-Ramos, 2021).

Methodological considerations

To our knowledge, this preliminary study is among the first to compare multiple computational models of repeated

vertical jump performance (Bosco, MG, and MGM-15) with directly measured ergometer power outputs. This comparative approach helps quantify the magnitude of methodological discrepancies rather than attempting validation. The consistent alignment between MGM-15 and ergometer results suggests that refined temporal modelling can narrow the gap between theoretical and empirical values. From a methodological standpoint, these pivotal findings highlight that classical computational models, such as Bosco and MG, systematically overestimate average power due to inherent simplifications in their formulas. By contrast, the MGM-15 model, which accounts for both flight and contact times, provides estimates that closely match direct ergometer measurements, offering a closer approximation of cyclic mechanical efficiency.

Practical implications

From an applied perspective, these findings help clarify how jump-based power estimates should be interpreted in everyday practice. Classical equations such as Bosco and Miron Georgescu remain useful for monitoring relative changes within the same athlete over time; however, their computational limitations and systematic calculation errors have already been documented in previous studies (Geantă & de Hillerin, 2025; Geantă et al., 2025). These documented inaccuracies raise important questions regarding the interpretation of average power values derived from these models, particularly when such values are implicitly assumed to reflect the athlete's actual mechanical or energetic output.

In contrast, the MGM-15 model yielded more conservative estimates that, within this exploratory sample, were closer to ergometer-derived power values. This difference arises from the integration of both flight and contact times into the computational structure of the MGM-15 formula, which reduces the systematic overestimation of power observed in the Bosco and MG models. By constraining power values toward the magnitude of mechanical energy externalized during cyclic muscular work, the MGM-15 approach produces estimates that are closer, as a result, to those recorded by ergometer-based measurements. Importantly, jump-based computational models and ergometer assessments should be regarded as complementary rather than interchangeable, as they rely on different mechanical principles and modes of energy externalization.

Limitations and future directions

As with all research, this study has several limitations that should be considered when interpreting the findings. First, the preliminary nature of the investigation, including a small and homogenous sample of five participants, limits the generalizability of the results. Maintaining a consistent protocol with prior research (Geantă et al., 2025; Geantă & de Hillerin, 2025), ensured continuity within this research line, but future studies should include larger and various populations for strengthening the external validity and to enhance the robustness of comparisons. Second, additional factors that may influence discrepancies between computational models and direct measurements were not examined in this study.

These include muscle fiber composition, fatigue kinematics, and neuromuscular coordination. Longitudinal designs could determine whether MGM-15 values are sensitive to training-induced changes in mechanical efficiency, further expanding the interpretative relevance of this method in applied sport science. Also, the methodological extensions could improve cross-modality comparability and the rigor of quantitative analyses. Incorporating force-platform analyses as the biomechanical gold standard would allow verification instantaneous ground reaction forces and mechanical power during vertical jumps (Lake et al., 2018). While Monark cycle ergometers (Driss & Vandewalle, 2013) are widely used in cycling protocols, Concept2 ergometers were selected in this preliminary exploratory study due to their documented technical validity and measurement reliability in cycling and rowing protocols (Podstawski et al., 2025; Treff et al., 2022; Turner & Rice, 2021). Although no ergometer is without limitations, these instruments provide standardized mechanical measurements that can serve as reference points for comparisons with computational models. Future research combining these methodological improvements with larger, more heterogeneous samples will allow for a more rigorous quantification of discrepancies among computational, kinetic, and ergometric approaches.

Conclusions

This preliminary exploratory study demonstrates that methodological choice substantially influences lower-limb power estimates derived from repeated vertical jump tests. Classical computational models, such as Bosco and Miron Georgescu, produced systematically higher power values compared with direct ergometer measurements, highlighting inherent limitations in their calculation assumptions. In contrast, the MGM-15 model, which integrates both flight and contact times, yielded more conservative estimates that were closer in magnitude to ergometer-derived power outputs, reflecting a closer approximation of the mechanical energy externalized during cyclic muscular work. These findings underscore the importance of critically evaluating and standardizing jump-based power calculation models, with particular attention to their computational structure. Given the preliminary nature of the study, further research using larger and more diverse samples is required to confirm these methodological observations.

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Conflict of interests

The authors declare no conflicts of interest related to this study.

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Cultivating Universal Values through Physical Education Pedagogy

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Abstract

This study aimed to ascertain the function of physical education instructors in the integration of universal ideals within educational institutions via physical education. This research employs a quantitative methodology utilizing a comparative study approach. This study involved 169 physical education teachers across different educational levels, comprising 113 males and 56 females. The instrument used in this study is the Universal Values in Sport Instrument (UVSI). This instrument uses 5 dimensions and there are 23 indicators. The gender evaluation indicates a significance value greater than 0.05, signifying that there is no discernible difference between male and female teachers in the implementation of universal principles. Similarly, the results of the level evaluation indicate a significance value greater than 0.05, suggesting that both bachelor's and master's level educators possess comparable capabilities in the integration of universal values within physical education. Thus, training or professional development programs that focus on strengthening the teaching of universal values should be provided evenly to all physical education teachers. Furthermore, school policies can facilitate a uniform strategy for cultivating student character through physical activity, irrespective of the teacher's educational background or gender.

Keywords: *sports pedagogy, ethical learning, teacher professionalism, value-based teaching, student character formation*

Introduction

Physical education teachers play an important role in shaping their students' moral development (Dinghua, 1997; Guan, 2023). Through structured activities and sportsmanship, they can instill important values such as teamwork, respect, and perseverance, which are crucial for holistic development in students' lives (Freire et al., 2018; Görgüt & Tutkun, 2018; Roux & Dasoo, 2020). Moreover, the integration of value-based education in the physical education curriculum can provide a comprehensive framework that not only addresses physical fitness but also fosters character development, allowing students to cultivate discipline, honesty and resilience in their daily interactions and challenges (Mar et al., 2023; Roux & Dasoo, 2020; Sullivan, 2007). Moreover, physical education teachers must also embody and promote these universal values themselves, as their own moral qualities and

teaching philosophies significantly influence students' perception and adoption of these values in sporting and academic contexts (Freire et al., 2018; Pennington, 2017; Xionghuai, 2014). Furthermore, an emphasis on a collaborative approach to teaching physical education may increase the effectiveness of instilling these values, as qualified educators can counteract the decline in moral standards by incorporating values-based principles into their training strategies and lesson plans, thus creating an environment that nurtures insightful individuals (Guan, 2023; Inna, 2020; Roux & Dasoo, 2020).

Physical education teachers should have a deep understanding of the purpose and importance of their subject, realizing that their role goes beyond mere physical fitness and sports skills. Their responsibilities include fostering students' physical fitness and the formation of a sporting spirit, which are fundamental to the educational process and should be

approached with seriousness and dedication (Guan, 2023; Li, 2020; Li & Deng, 2022). Thus, physical education teachers can effectively influence students' moral development while emphasizing the importance of physical education as an essential component of a well-rounded education (Gallego et al., 2020; Guan, 2023; Li, 2020; Zhao et al., 2022). To achieve this, it is important for physical education teachers to establish themselves as role models with noble moral qualities, as their attitudes and behaviors can have a great impact on students' understanding and appreciation of these universal values (Doolittle & Demas, 2001; Freire et al., 2018; Görgüt & Tutkun, 2018; Guan, 2023). Through deliberate pedagogical strategies that emphasize the connection between physical education and moral development, teachers can create experiences that not only enhance students' physical abilities but also promote important ethical values that contribute to their overall character formation (Freire et al., 2018; Guan, 2023; Muhtar et al., 2020; Zhao et al., 2022). This approach entails a deliberate focus on integrating ideological and moral education within the physical education curriculum, ensuring that each activity serves as a conduit for teaching fundamental ethical principles and encouraging students to embrace values that extend beyond the classroom and into their wider lives (Guan, 2023; Liu & Hu, 2020; Miller & Jarman, 1988).

This alignment between physical education and moral education not only enriches the educational experience but also prepares students to engage meaningfully in society, as they develop not only their physical skills but also their ethical framework and social responsibility (Balan et al., 2012; Guan, 2023; Miguel et al., 2023). In this context, the integration of moral education in physical education becomes particularly important, as it enriches the curriculum and emphasizes the development of students' ideological will and moral character alongside their physical abilities, thereby redefining the purpose of physical education in a way that aligns with the holistic goals of education in the modern era (Guan, 2023; Xionghuai, 2014; Zhao et al., 2022). In this endeavor, it becomes increasingly important for educators to employ effective teaching methods that foster a conducive learning environment, where values such as discipline and teamwork are not only taught but actively practiced through engaging physical activities, thus contributing to a strong moral education framework that is seamlessly woven into the physical education curriculum (Roux & Dasoo, 2020; Wang, 2011).

Research has shown that physical education teachers can play an important role in instilling universal values to students (Guan, 2023; Xionghuai, 2014; Zhao et al., 2022). By implementing character education in their lesson plans and fostering an environment that emphasizes cooperation and respect during physical activity, educators can significantly impact students' moral development in ways that go beyond physical fitness alone (Pennington, 2017; Suherman, 2018; Sullivan, 2007). This dual focus on the development of physical skills and moral character can lead to increased student engagement, better interpersonal relationships among peers, and the development of virtues that students carry throughout their lives, making physical education an essential component of character education in contemporary schools (Adu,

2023; Xionghuai, 2014; Zhao et al., 2022). The integration of moral education into the physical education curriculum is a key strategy in this regard, as it allows for the deliberate embedding of value-based principles into the learning process. This approach recognizes the inherent link between physical education and the development of important life skills, such as teamwork, discipline, and resilience, which are not only beneficial for success in sport but also contribute to students' overall moral and social growth (Bailey, 2006; Mar et al., 2023; Opstoel et al., 2020). Moreover, effective teaching methods that prioritize experiential learning can create opportunities for students to practice these values in real-world situations, further reinforcing their importance and relevance in daily life, thus achieving the goal of moral education alongside physical education (Wang, 2011; Xionghuai, 2014).

Physical education teachers are uniquely positioned to foster an environment that supports physical activity and moral development, acting as a catalyst to instill universal values in students through targeted teaching methods and curriculum integration, ultimately shaping them into responsible and insightful individuals (Suherman, 2018; Wang, 2011; Xionghuai, 2014; Zhao et al., 2022). This multifaceted approach is not only in line with contemporary educational reforms, but also responds to the growing need for character education in a society facing moral and ethical challenges, underscoring the integral role that physical education can play in cultivating a generation equipped with physical prowess and moral fortitude. In this regard, the recognition of physical education as an important vehicle for moral education becomes all the more relevant, as it emphasizes the transformative potential of physical activity in fostering virtues such as integrity, justice and perseverance among students, thereby promoting a holistic educational framework that prepares them for meaningful engagement in their communities and the world at large (Naylor & Yeager, 2013). Research shows that fostering an environment conducive to moral development during physical education is not only beneficial, but essential, as it creates a culture of respect and cooperation that extends beyond the physical activity itself, ultimately supporting the creation of well-rounded individuals who embody the values necessary for academic and social success (Balan et al., 2012; Butler, 2000). This suggests that the role of physical education teachers goes far beyond simply teaching sports skills; it includes the important responsibility of shaping students' moral frameworks and instilling universal values that are critical to their development as conscious citizens in a complex and interconnected world (Jones, 2005).

Furthermore, as physical education teachers embody and model these values through their own behavior, they provide a powerful example for students to emulate, thereby strengthening the link between physical activity and moral character development, which is critical in building a foundation for responsible citizenship in an ever-evolving social landscape (Gordon, 2010; Pennington, 2017). In this context, it is imperative for physical education programs to not only focus on improving physical abilities, but also comprehensively incorporate character education, which serves to bridge the gap between fitness and ethical behavior development,

promoting an environment conducive to nurturing moral individuals equipped to face the challenges of the 21st century (Liu & Hu, 2020; Suherman, 2018; Zhang, 2018).

Several studies have explored the relationship between physical education and moral or value-based education. Participation in physical activity has been shown to contribute to social and moral development (Bailey, 2006), while sport-based programs can enhance students' interpersonal and emotional skills when implemented through well-structured pedagogical models (Opstoel et al., 2020). Integrating moral principles into teaching practices has also been found to positively influence students' ethical reasoning and cooperation skills (Roux & Dasoo, 2020). Furthermore, teachers who intentionally embed moral instruction in physical education tend to produce stronger behavioral outcomes in students, including fairness, respect, and responsibility (Muhtar et al., 2020). Value-oriented physical education has likewise been emphasized as a tool for character education when teachers act as role models and employ reflective teaching strategies (Suherman, 2018).

Despite increasing attention to the integration of moral education in physical education, most previous research has primarily focused on student outcomes rather than examining teachers' roles and implementation strategies (Guan, 2023; Zhao et al., 2022). There remains limited empirical evidence comparing how teacher characteristics such as gender or educational background affect the implementation of universal values within physical education contexts (Zhao et al., 2022). While previous studies have highlighted the importance of teacher competence and moral orientation in values-based instruction (Guan, 2023), quantitative evidence differentiating these influences across teacher demographics remains scarce. In addition, few studies have utilized standardized measurement instruments, such as the Universal Values in Sport Instrument (UVSI), to assess how these values are practiced and internalized in educational settings.

Therefore, this study aims to fill this gap by examining the role of physical education teachers in implementing universal values through a quantitative comparative approach. Specifically, the study investigates (1) the differences in the implementation of universal values through physical education based on teachers' gender, and (2) the differences based on teachers' education level. By addressing these aspects, this research contributes empirical insights into how teacher-related factors influence the enactment of moral and ethical values in physical education settings. The findings are expected to inform teacher development programs and school policies that promote equitable and effective moral education practices across diverse educational contexts.

Material and methods

Study design and participants

This research utilized a comparative study design to evaluate the implementation of physical education in schools alongside the application of universal values by educators. The sample comprised 169 physical education instructors, categorized by gender 113 males and 56 females and by educational

attainment 148 holding bachelor's degrees and 21 possessing master's degrees.

Instrument

This research uses the Universal Values in Sport Instrument (UVSI). This instrument uses 5 dimensions and there are 23 indicators. Dimensions of Universal Values: Ethics and Morals (respect for the rules, respect for others, fair play, self-esteem, honesty, tolerance); Knowledge and understanding (problem solving, understanding, how to win, how to lose); Social (cooperation, communication, connecting with others, teamwork, trust); Psychological (value of effort, resilience, confidence, discipline, self-respect); Leadership and Organization (leadership, how to manage competition, sharing) (Purnomo et al., 2024). The instrument has met the criteria for use with a Cronbach's Alpha value of 0.990.

Statistical analysis

Data were evaluated utilizing Analysis of Variance (ANOVA) to investigate significant differences in instructors' engagement according to gender and educational attainment. All statistical analyses were performed utilizing IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). The threshold for statistical significance was established at $p < 0.05$.

Ethics

This study was deemed ethically appropriate in accordance with the seven WHO (2011) Standards: (1) Social Values, (2) Scientific Values, (3) Equitable Assessment and Benefits, (4) Risks, (5) Persuasion/Exploitation, (6) Confidentiality and Privacy, and (7) Informed Consent, as outlined in the 2016 CIOMS Guidelines. This is demonstrated by the attainment of the criteria for each standard. The Declaration of Ethics received approval from the Health Research Ethics Committee of Universitas Negeri Malang (Approval No. 16.07.1/UN32.14.2.8/LT/2024), effective from July 16, 2024, to July 16, 2025. Before data collection, each participant was apprised of the study's purpose and objectives and granted signed consent to participate.

Results

Results of developing universal values through physical education based on gender

This section provides a comparative investigation of the development of universal values among male and female physical education teachers. This overview presents the findings of the Independent Samples t-test, which assesses the impact of gender differences on the application of universal values across numerous key aspects, as illustrated in table 1 below.

According to table 1, the descriptive statistics indicate that male and female physical education teachers exhibit remarkably similar performance across all aspects of universal values. In the Ethics and Morals dimension, male teachers achieve an average score of 77.56 (SD=7.02), closely resembling the score of female instructors at 77.59 (SD=5.48). In

Knowledge and Understanding, males achieve a score of 75.91 (SD=7.25), marginally surpassing girls who score 74.64 (SD=7.44). The Social dimension exhibits comparable outcomes, with male educators averaging 88.88 (SD=6.72) and female educators 89.29 (SD=6.67). In the Psychological dimension, male teachers have a score of 87.23 (SD=8.02), while

female teachers score 86.71 (SD=8.17). In Leadership and Organization, men educators have an average score of 44.84 (SD=4.88), but female educators average 44.23 (SD=5.01). The constantly minor discrepancies suggest that both groups have comparable levels of universal values application.

Table 1. Results of independent samples t-test on universal values development based on gender

	Male		Female		df	t	p	Cohen's d
	M	SD	M	SD				
Ethics and Morals	77.56	7.02	77.59	5.48	136	-0.03	0.98	-0.01
Knowledge and understanding	75.91	7.25	74.64	7.44	107	1.06	0.29	0.17
Social	88.88	6.72	89.29	6.67	110	-0.37	0.71	-0.06
Psychological	87.23	8.02	86.71	8.17	107	0.39	0.70	0.06
Leadership and Organization	44.84	4.88	44.23	5.01	107	0.76	0.45	0.12

The t-test results presented in table 1 corroborate these descriptive findings. All p-values above 0.05, indicating no statistically significant differences between genders. In Ethics and Morals, the t-value is -0.03 with a p-value of 0.98, corroborated by a negligible effect size (Cohen's d=-0.01), signifying an almost imperceptible difference. In Knowledge and Understanding, t=1.06 and p=0.29, indicating a small effect size (d=0.17), which further implies a negligible practical difference. The Social dimension indicates t=-0.37, p=0.71, and d=-0.06, demonstrating a minor influence. The Psychological dimension yielded t=0.39, p=0.70, and d=0.06, signifying a very minor and inconsequential difference. Finally, in Leadership and Organization, the t-value is 0.76, the p-value is 0.45, and the effect size is minimal (d=0.12).

In summary, both the statistical differences and effect sizes indicate that male and female teachers apply universal values at nearly equivalent levels, with all Cohen's d values residing within the negligible to very small range, thereby affirming that gender does not significantly affect the implementation of universal values across the five dimensions.

Results of developing universal values through physical education based on education level

The subsequent section summarizes the comparison

of universal values development between educators holding Bachelor's and Master's degrees. This overview presents the findings of the Independent Samples t-test, which investigates the correlation between education level and the discrepancies in instructors' application of universal values across multiple dimensions, as illustrated in Table 2 below.

According to Table 2, the descriptive data indicate that educators possessing Bachelor's and Master's degrees exhibit comparable performance across all five dimensions of universal values. In Ethics and Morals, educators with a Bachelor's degree have an average score of 77.45 (SD=6.58), but those with a Master's degree achieve an average score of 78.38 (SD=6.27). In Knowledge and Understanding, the groups are almost indistinguishable, with Bachelor's score 75.51 (SD=7.39) and Master's scoring 75.33 (SD=6.93). In the Social dimension, Bachelor's degree educators have an average score of 89.16 (SD=6.77), but Master's degree educators average 88.05 (SD=6.10). The psychological dimension is almost indistinguishable, with Bachelor's educators score 87.07 (SD=8.15) and Master's educators scoring 87.00 (SD=7.47). Bachelor's degree holders in Leadership and Organization achieve a score of 44.68 (SD=4.98), whereas Master's degree holders attain a score of 44.33 (SD=4.60). These findings indicate negligible disparities among educational levels.

Table 2. Results of independent samples t-test on universal values development based on education level

	Male		Female		df	t	p	Cohen's d
	M	SD	M	SD				
Ethics and Morals	77.45	6.58	78.38	6.27	26.66	-0.61	0.54	-0.14
Knowledge and understanding	75.51	7.39	75.33	6.93	26.87	0.11	0.91	0.03

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Table 2. Results of independent samples t-test on universal values development based on education level

	Male		Female		df	t	p	Cohen's d
	M	SD	M	SD				
Social	89.16	6.77	88.05	6.10	27.49	0.71	0.48	0.16
Psychological	87.07	8.15	87.00	7.47	27.22	0.04	0.97	0.01
Leadership and Organization	44.68	4.98	44.33	4.60	27.10	0.30	0.76	0.07

The inferential results shown in Table 2 indicate that these discrepancies lack statistical significance. All t-values are confined within a limited spectrum from -0.61 to 0.71 , with associated p-values beyond 0.05 (Ethics and Morals: $p=0.54$; Knowledge and Understanding: $p=0.91$; Social: $p=0.48$; Psychological: $p=0.97$; Leadership and Organization: $p=0.76$). The Cohen's d values across all dimensions demonstrate negligible effect sizes, reinforcing the lack of significant differences. The effect sizes are -0.14 for Ethics and Morals, 0.03 for Knowledge and Understanding, 0.16 for Social, 0.01 for Psychological, and 0.07 for Leadership and Organization, all categorized as negligible to very tiny. This indicates that the observed differences in mean scores between teachers holding Bachelor's and Master's degrees are minimal and lack practical significance.

The aggregated descriptive and inferential results indicate that educators holding Bachelor's and Master's degrees use universal values in physical education at similar levels, with no statistically or practically significant differences across all five variables.

Discussion

The findings of this study indicate that gender does not significantly influence the application of universal values in physical education. The statistical results show that the average scores in the five dimensions of male and female teachers are almost identical: Ethics and Morals (77.56 vs. 77.59), Knowledge and Understanding (75.91 vs. 74.64), Social (88.88 vs. 89.29), Psychological (87.23 vs. 86.71), and Leadership and Organization (44.84 vs. 44.23). All t-test results show $p>0.05$, such as Ethics and Morals ($t=-0.03$, $p=0.98$, $d=-0.01$), which explains that there is no difference between males and females in the application of universal values in PE. These results align with previous studies showing that gender does not significantly influence teachers' ethical practices due to standard expectations in PE teaching (Bronikowska et al., 2019). Although some research findings suggest that female teachers are more likely to exhibit a more relational value orientation (Temel et al., 2022), the quantitative data and the minimal numerical differences in these findings suggest that Physical Education teachers share the same professional moral commitment regardless of gender, which may be influenced by uniform curriculum guidelines that emphasize fairness, respect, and sportsmanship (Aydin, 2024; Haerens et al., 2011; Raj & Prasad, 2023).

Meanwhile, the results showed that differences in educational level did not significantly influence the implementation of universal values by PE teachers in schools. Descriptive analysis showed that teachers with Bachelor's and Master's degrees achieved almost the same average scores in all dimensions: Ethics and Morals (77.45 vs. 78.38), Knowledge and Understanding (75.51 vs. 75.33), Social (89.16 vs. 88.05), Psychological (87.07 vs. 87.00), and Leadership and Organization (44.68 vs. 44.33). Inferential statistics did not confirm significant differences, as the p-values obtained ranged from 0.48 to 0.97 , such as Psychological ($t=0.04$, $p=0.97$, $d=0.01$). These findings support research showing that teaching competence is not solely shaped by academic qualifications, but also by ongoing practice and professional culture (Guan, 2023; Roux & Dasoo, 2020). Although other research has found that further education can improve ethical reasoning (Blaich et al., 2023), the results of the calculation of negligible effect sizes in this study (all $d<0.20$) indicate that there is no difference in the level of education in the application. This also has similarities with the results in the section above regarding gender which also states that gender differences do not affect the results of the application of universal values, all depending on how the development of moral-pedagogical skills is more in-depth and more effective application.

Consistent statistical equality across groups indicates that the implementation of universal values in Physical Education is more influenced by teachers' professional experience and consistency in implementing universal values through physical education. Teachers' backgrounds, regardless of gender or degree, operate within the same professional framework of educators and teachers in schools, prioritizing ethical behavior and social development. Physical Education's content, which incorporates experiential learning through teamwork and collaborative activities, creates alignment in values-based outcomes, as demonstrated by the high and tightly clustered mean scores on the social dimension ($88.88-89.29$). These results align with the view that moral skills in Physical Education emerge through modeling, classroom interactions, and reflective practice, rather than from personal characteristics or academic hierarchies (Li, 2020; Naylor & Yeager, 2013).

In this study, the above figures are of particular interest to teachers and policymakers, who should better understand and comprehend teacher needs. This is not limited to physical education teachers being male or even having a master's degree, but also to the competency, desire, and persistence

in implementing a quality physical education program. The narrow range of scores and consistently small effect sizes may be due to the program's homogeneity and the limited or even small sample size. Furthermore, data obtained from self-assessments may also inflate the averages for moral-based constructs due to social desirability tendencies. Furthermore, contextual influences such as leadership support, peer collaboration, and student behavior were not analyzed, although these influences may explain subtle variations in value implementation (Zhao et al., 2022). Because this study was limited to a single geographic region, future research should include a larger and more diverse sample, while integrating observational assessments and longitudinal tracking to capture how teachers' universal value practices evolve over time.

Conclusions

This study's findings indicate that the use of universal values in physical education reveals no statistically significant variations related to the gender or educational level of teachers. The independent samples test indicated that all five dimensions ethics and morals, knowledge and understanding, social, psychological, and leadership and organization exhibited p-values over 0.05, signifying equivalent performance across all instructor groups. The t-values varied from -0.608 to 0.709 for education level and from -0.030 to 0.756 for gender, indicating that both male and female educators, as well as those with bachelor's and master's degrees, demonstrate comparable efficacy in fostering universal ideals.

The results indicate that the incorporation of moral and ethical training in physical education is uniformly applied across teacher demographics, demonstrating a consistent pedagogical approach within the educational system. Consequently, professional development programs must be developed inclusively, guaranteeing that all educators irrespective of gender or academic credentials obtain equitable support in enhancing value-based educational practices. The study emphasizes the collective efficacy of the physical education profession in promoting universal values and establishes a basis for future research to investigate contextual or cultural elements that may further improve moral learning results. The findings indicate that educational policymakers and curriculum creators ought to integrate universal value education more systematically into physical education programs at all educational tiers.

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Conflicts of Interest

No potential conflicts of interest relevant to this article could be reported.

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Effects of Adaptive Riding on Children with Cerebral Palsy

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Abstract

This study investigated the effects of adaptive riding exercise on specific physical parameters in children with cerebral palsy (CP). Twenty children with CP (ages 8–12 years) were randomly assigned to an experimental group (n=10) or a control group (n=10). The intervention involved a 12-week adaptive riding program, consisting of 30–45 minute sessions, three times per week, led by a certified instructor and supported by specially trained horses and volunteer university students. Data collection, executed via pre- and post-intervention assessments, focused on parameters including leg-back strength, unilateral-bilateral flexibility, accuracy, linearity, maximal grip force, and the rate of grip force development. Data were analyzed using a mixed-model ANOVA. The experimental group demonstrated statistically significant improvements over the control group in several measures, including hand-eye coordination, maximal grip strength, flexibility, and muscle strength. The findings suggest that adaptive riding exercise provides a supportive therapeutic effect for children with CP, specifically those classified as GMFCS Levels II and III. Therefore, it is recommended that children with CP who are GMFCS levels 2 and 3 participate in adaptive riding programs.

Keywords: *adaptive horseback riding, cerebral palsy, equine-assisted exercise, equine-assisted services, motor performance, disabled sport*

Introduction

Cerebral palsy (CP) is an umbrella term that describes permanent movement and posture disorders causing activity limitations. These conditions are attributed to non-progressive disturbances that occur in the developing fetal or infant brain (Sadowska, Sarecka, & Kopyta, 2020). Motor impairments resulting from cerebral palsy frequently induce disturbances in sensation, perception, cognition, communication, and behavior (Paul, Nahar, Bhagawati, & Kunwar, 2022). These impairments can also result in epilepsy and secondary musculoskeletal problems (Ruiz Brunner & Cuestas, 2019). The condition is characterized by numerous risk factors, specific etiologies, symptoms, the degree of functional limitations, and the development and severity of associated and secondary conditions (Sadowska et al., 2020). The treatment options for this condition are numerous, and the course of the condition can evolve over time (Patel et al., 2024).

The overarching objective of CP therapeutic strategies is twofold: first, to mitigate the impact of disability, and second, to enhance physical, cognitive, and communicative abilities. Conventional treatment modalities, including physical ther-

apy, orthopedic interventions, and neurological care, remain integral to the management of these conditions. However, their efficacy in achieving long-term functional outcomes is often constrained (Booth et al., 2018; Kousar, Sultana, Sultana, Banu & Begum, 2023). According to Liptak's (2005) findings, children diagnosed with CP frequently exhibit a multitude of symptoms for which there is no known curative treatment. Consequently, these families often seek alternative treatments and therapeutic interventions from various sources. In the aforementioned study, "equine-assisted therapy" is identified as one of a series of methods classified within the domain of Complementary and Alternative Medicine (CAM).

Equine-related human services have undergone significant diversification and expansion in recent decades (Wood et al., 2021). Following extensive deliberations on terminology and subsequent revisions, a comprehensive consensus has been achieved regarding the categorization of equine-related human services. Within this framework, a total of 12 distinct service types have been identified and classified under the subcategories of "therapy," "learning," and "horsemanship," collectively referred to as Equine-Assisted Services (EAS) (Wood et al., 2021).

Within this classification, the term adaptive riding is included under the “Equestrian” category and is used to describe horseback riding activities that are modified to accommodate the physical, cognitive, or emotional needs of individuals with diverse abilities. This terminology is consistent with the language used in the fields of adaptive recreation and sport, emphasizing that the activity is adapted to the rider rather than requiring the rider to conform to a standardized form of riding (Lassell, Wood, Schmid & Cross, 2021; Wood et al., 2021). Additionally, the literature reveals a paucity of studies examining the relationship between adaptive riding and cerebral palsy, indicating a clear need for further research in this area.

Given all these information, the aim of this study was to investigate the effects of adaptive riding exercises on specific parameters in children with cerebral palsy.

Methods

This study employed an experimental, pretest-posttest design with two-time repeated measurements applied to both the experimental and control groups.

Participants

A request for participation was extended to children diagnosed with cerebral palsy (CP) in the Nevşehir province. The determination of eligibility was based on the following inclusion and exclusion criteria:

Inclusion criteria included: age 8–12 years; under physician/therapist supervision; classification at GMFCS Level II or III; ability to follow verbal instructions; and no prior horse experience.

Exclusion criteria included: severe visual or hearing impairment; animal phobia (especially horses); allergies; uncontrollable epileptic seizures; or surgery within the last year.

Interviews were conducted with families, physicians, and teachers of potential participants. Children who met all inclusion criteria and whose families provided written informed consent were enrolled in the study. Participants were randomly assigned to either the experimental group (EG) or the control group (CG) using a fishbowl draw method. The experimental group consisted of six female participants (mean age: 9.83 (± 1.60) years) and four male participants (mean age: 10.50 (± 1.29) years). The control group consisted of five female participants (mean age: 10.00 (± 1.58) years) and five male participants (mean age: 10.60 (± 1.14) years). Ethics Committee approval was secured from Erciyes University (Decision No: 2016/180, March 4, 2016).

Participant Characteristics: All participants exhibited mild intellectual disability. The experimental group (EG) comprised six girls and four boys, while the control group (CG) included five girls and five boys. Gross Motor Function Classification System (GMFCS) levels were distributed as follows: the EG included four children classified as GMFCS level II and six as level III, whereas the CG included five children classified as level II and five as level III (Palisano et al., 1997).

Horses: Five horses were selected based on criteria including temperament, strength, health, and size. The horses

underwent a 12-week preparatory training program to enhance tolerance and desensitize them to sudden noises, foreign objects, and mobility aids (walkers, crutches). Training also ensured mounting/dismounting capability from both sides. Horses participated in a maximum of four sessions per day, though typically trained three times, representing a light workload.

Intervention

Adaptive Riding Program: The intervention spanned 12 weeks, with the experimental group (EG) participating in 30–45 minute adaptive riding sessions, three days per week. The program was designed based on general principles of adaptive riding and equine-assisted interventions described in the literature, incorporating individualized progression and professional supervision (Sterba, 2007; Wood et al., 2021). Sessions were conducted individually by a certified adaptive riding instructor and supported by relevant specialists (e.g., motor control specialist, physiotherapist), who were either present during sessions or provided professional consultation.

Equestrian equipment (saddle, reins, stirrups, mounting platform) was individually adapted for each child. Session plans were tailored to each participant, taking into account ongoing rehabilitation and school schedules. In addition, children were encouraged to participate in up to 10 minutes of preparatory and horse care activities before and after each session, under supervision of the instructor or trained volunteers.

Control Group Condition: The control group (CG) did not participate in any form of hippotherapy, adaptive riding, equine-assisted activities, or other horse-related interventions during the study period. Participants in the CG continued their standard rehabilitation programs, which typically consisted of conventional physiotherapy and/or occupational therapy sessions prescribed by their healthcare providers. These programs were maintained at their usual frequency and duration (2–3 sessions per week, approximately 30–45 minutes per session) throughout the 12-week study period.

Importantly, the CG did not engage in any additional structured physical activity or exercise programs beyond their routine rehabilitation and school-based activities during the intervention period.

Measurement tools and procedures

Data were collected during pre-test and post-test assessments using specialized equipment to measure key physical parameters.

Arm-Reaching Movement Performance (Accuracy and Linearity):

The KineReach system (EZ Kinetics, State College, PA), a custom-developed experimental setup originally described by Przybyla et al. (2013) and subsequently used in later studies (e.g., Cortes et al., 2017), was used to evaluate arm extension movements in a virtual environment (Figure 1).

Participants sat in a custom chair, with an electromagnetic sensor (TrackSTAR Ascension Technology, USA) attached to the index finger (Sainburg & Wang, 2002). Visual targets were displayed on an HD television reflected in a mir-

ror (Figure 1a). A MATLAB R2013a program (MathWorks Inc., Natick, USA) provided visual feedback and recorded data at 100 Hz. The task required children to reach for three randomly located targets (positioned at 30°, 60°, and 90° from the starting point, 20 cm away) with both the right and left

hands to measure accuracy and linearity (Figure 1b). Movement onset was signaled visually and audibly after maintaining contact with the starting point for 300 ms (Beyaz, Akpınar, & Demirhan, 2024).

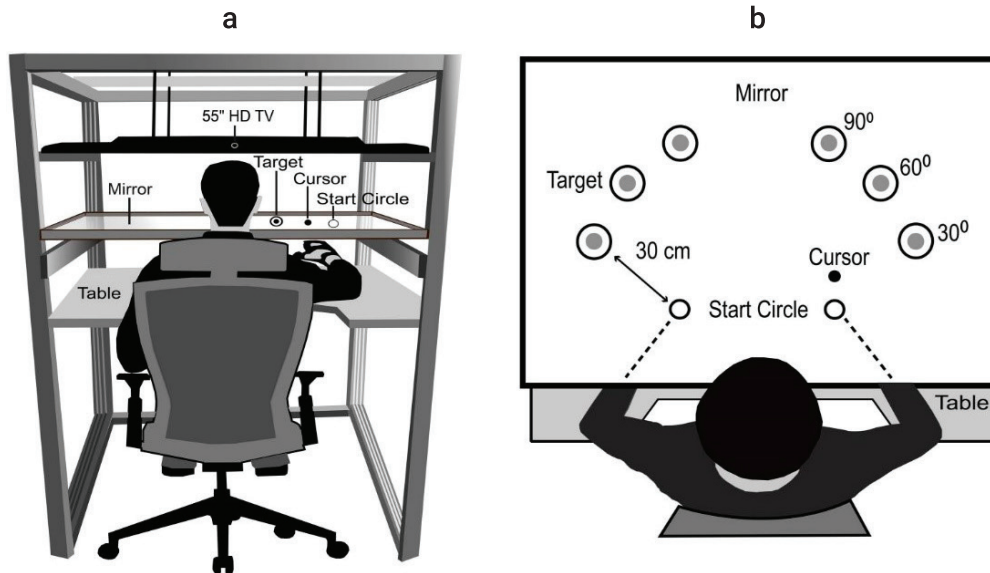


Figure 1. a: KineReach system; b: Targets distribution.

Maximal Grip Force (Max. GF) and Rate of Grip Force Development (RGFD): A SML-900N force transducer (Interface, Scottsdale, Arizona, USA) was used to measure both maximum grip force and the maximal rate of grip force development (RGFD). Participants were seated with their forearms supported and elbows flexed at 90°. For Max. GF, subjects squeezed the device maximally for 5–6 seconds. For Max. RGFD, subjects squeezed as forcefully and rapidly as possible for 5–6 seconds, with the RGFD value recorded within the initial 0–300 ms (Akpınar, 2016; Beyaz, Akpınar & Demirhan, 2024; Sainburg & Wang, 2002). Three trials were performed for each hand, separated by a one-minute rest, and the highest value was used.

Back – Leg Strength: The Takei (Japan) digital leg-back dynamometer (Takei Instruments Ltd, Tokyo, Japan) was used. Participants stood on the platform with knees bent, grasping the bar, and were instructed to pull vertically upwards using maximal back and leg effort. The best result from three trials was recorded in kilograms (Coldwells, Atkinson, & Reilly, 1994).

Flexibility: The experimental apparatus utilized was a portable Baseline Sit-And-Reach Flexibility Box (Baseline®, New York, USA). The measurement of unilateral flexibility (right and left hands separately) and bilateral flexibility (standard two-hand reach) was conducted. The optimal outcome of three successive trials was documented in centimetres (Hartman & Looney, 2003).

Data analysis

Statistical analysis was performed using the JMP Statistics program (JMP®, Cary, NC, USA). The significance level

was set at $p < 0.05$. Three-way interactive mixed-model ANOVA was employed to determine differences across groups (EG vs. CG), hands (Right & Left), and tests (Pre-test vs. Post-test) for maximum grip force, RGFD, unilateral flexibility, accuracy, and linearity. Two-way interactive mixed-model ANOVA was used for leg-back strength and bilateral flexibility variables (Groups-times-Tests). Assumptions were tested prior to analysis. Tukey's HSD post-hoc test was used to examine specific differences when significant interactions were found.

Results

Statistical analyses for all variables utilized a three-way or two-way interactive mixed-model ANOVA. Post-hoc analyses were performed using Tukey's Honestly Significant Difference (HSD) test when significant interactions were detected.

Accuracy: Figure 2 presents the results of a mixed-model ANOVA examining accuracy across three interacting factors. The analysis yielded a significant Group \times Test interaction, $F(1, 18) = 9.41$, $p = 0.006$, with a large effect size ($\eta^2 = 0.34$). Tukey's HSD post hoc comparisons indicated no significant difference between the experimental group ($M = 4.29 \pm 0.56$ cm) and the control group ($M = 4.90 \pm 0.52$ cm) at pretest, demonstrating comparable baseline performance. In contrast, the experimental group showed a substantial improvement at posttest ($M = 1.63 \pm 0.24$ cm), differing significantly from both its own pretest values and the control group's posttest scores ($M = 5.34 \pm 0.35$ cm). These findings reflect a robust intervention effect, indicating that the adaptive riding program produced a meaningful enhancement in accuracy performance (Figure 2).

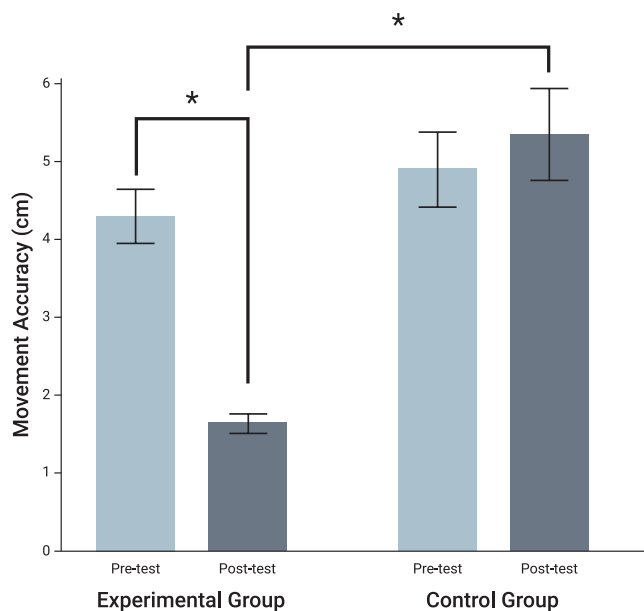


Figure 2. Changes in accuracy values across groups and tests

Linearity: The results of the mixed-model ANOVA examining the linearity parameter are presented in Table 1. The analysis examined the effects of Group (experimental vs. control), Hand (right vs. left), Test (pre-test vs. post-test), and their interactions. A significant main effect of Tests was observed ($F(1,18)=11.83, p=0.002, \eta^2=0.40$), indicating that linearity improved from pre-test to post-test, primarily in the

experimental group. No significant main effects were found for Groups or Hands, and the three-way interaction (Groups \times Hands \times Tests) was non-significant with a negligible effect size ($\eta^2 \approx 0.0001$). Two-way interactions showed medium-to-large effects: Groups \times Hands ($\eta^2=0.15$) and Groups \times Tests ($\eta^2=0.17$), while Hands \times Tests showed a medium effect ($\eta^2=0.07$); none of these reached statistical significance.

Table 1. Pretest and posttest linearity scores and mixed-model ANOVA results

Variables		N	$\bar{X} \pm SD$	F	p	Partial η^2
Group	EG	10	0.16 \pm 0.02	0.58	0.455	0.03
	CG	10	0.18 \pm 0.02			
Hand	RH	10	0.17 \pm 0.01	0.82	0.376	0.04
	LH	10	0.17 \pm 0.01			
Test	Pretest	10	0.19 \pm 0.02	11.83	0.002*	0.40
	Posttest	10	0.15 \pm 0.01			
Group * Hand	EG – RH	10	0.17 \pm 0.01	3.18	0.091	0.15
	EG – LH	10	0.16 \pm 0.02			
	CG – RH	10	0.17 \pm 0.02			
	CG – LH	10	0.19 \pm 0.01			
Group * Test	EG – Pretest	10	0.20 \pm 0.02	3.77	0.067	0.17
	EG – Posttest	10	0.13 \pm 0.02			
	CG – Pretest	10	0.19 \pm 0.02			
	CG – Posttest	10	0.17 \pm 0.02			
Hand * Test	RH – Pretest	10	0.18 \pm 0.01	1.40	0.252	0.07
	LH – Pretest	10	0.20 \pm 0.01			
	RH – Posttest	10	0.15 \pm 0.01			
	LH – Posttest	10	0.15 \pm 0.02			

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Table 1. Pretest and posttest linearity scores and mixed-model ANOVA results

	Variables	N	$\bar{X} \pm SD$	F	p	Partial η^2
Group * Hand * Test	EG – RH – Pretest	10	0.20±0.02	0.002	0.958	0.01
	EG – LH – Pretest	10	0.20±0.02			
	CG – RH – Pretest	10	0.17±0.01			
	CG – LH – Pretest	10	0.21±0.02			
	EG – RH – Posttest	10	0.14±0.02			
	EG – LH – Posttest	10	0.12±0.02			
	CG – RH – Posttest	10	0.16±0.01			
	CG – LH – Posttest	10	0.18±0.01			

Overall, these results suggest that the primary improvement in linearity was driven by test sessions, with the experimental group showing the most notable gains, while other factors and interactions contributed minimally.

Maximum Grip Force (Max. GF): A three-way interaction mixed model ANOVA statistical analysis of the pretest and posttest data for the maximum grip force of the right and left hands of the EG and CG groups revealed no interaction between groups, tests, and hands. Concurrently, no significant differences were observed between Groups x Hands, and Hands x Tests. However, a substantial difference was identified between the groups (EG and CG) x tests (pre-test and post-test), ($F(1,18)=8.33$, $p<0.05$). As demonstrated in Figure 3a, which reflects the Tukey HSD analysis, a statistically significant difference is evident between the pre-test ($\bar{X}=80.37 \pm 15.23$ N) and post-test ($\bar{X}=115.48 \pm 15.04$ N) of the EG group.

Rate of Grip Force Development (RGFD): In order to analyse the pre-test and post-test data on the maximum rate of grip force development (RGFD) of the right and left hand in the experimental and control groups, a three-way interaction mixed model ANOVA was employed. A three-way interaction was not found. In addition, there was an absence of

evidence to suggest a group x hands interaction, nor was there any indication of a hands x tests interaction. Nevertheless, a significant difference was found in the groups (EG-CG) x tests (pre-test-post-test) interaction, ($F(1, 18)=5.40$, $p<0.05$). Tukey HSD analysis revealed a statistically significant difference in RFGD between the pre-test ($\bar{X}=360.31 \pm 75.31$ N/s) and post-test ($\bar{X}=501.83 \pm 74.45$ N/s) results of the EG group (Figure 3b).

Back – Leg Strength: A 2-interactive mixed model ANOVA statistical analysis method was used in the statistical analysis of the Back-Leg Strength variable. Because the device used for the measurement did not provide strength values less than 20 kg, 3 people from the experimental group and 2 people from the control group could not take the measurement. As a result of the analysis, a significant difference was found between groups (experimental - control) x tests (pre-test - post-test), $F(1, 13)=37.2$, $p<0.05$. According to Tukey HSD analysis, the post-test (Mean= 48.81 ± 8.11 kg) values of the experimental group were found to be statistically significantly different from its own pre-test values (Mean= 33.6 ± 4.08 kg) and from both the pre-test (Mean= 29.48 ± 4.78 kg) and post-test (Mean= 30.63 ± 5.58 kg) values of the control group (Figure 3c).

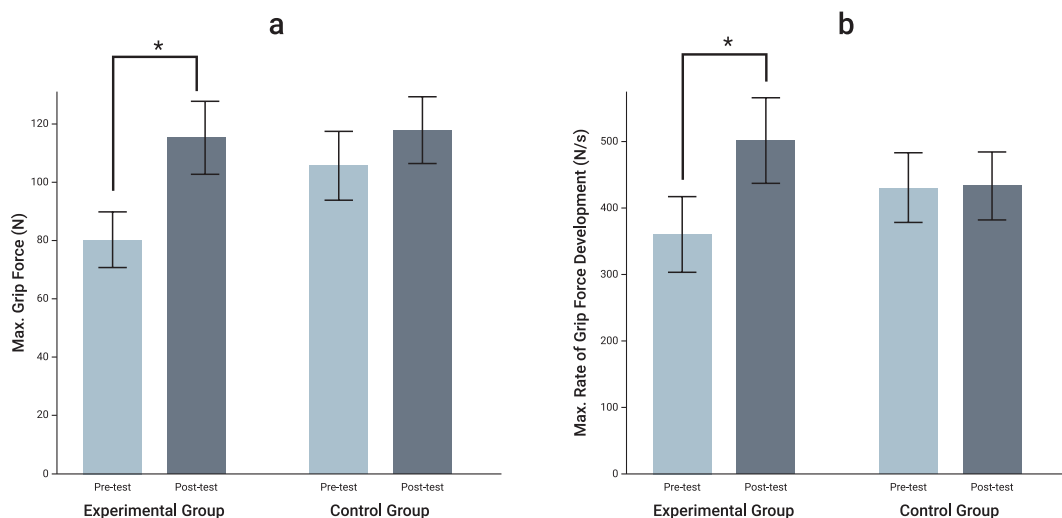
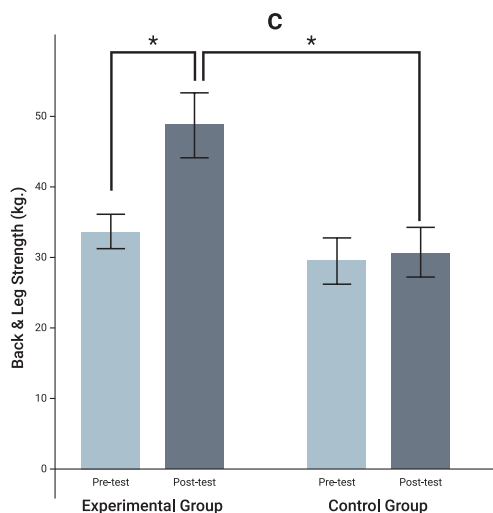


Figure 3. Changes in strength measures, a: maximum grip force, b: max. rate of grip force development, and c: back-leg strength in experimental and control groups following the intervention



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Figure 3. Changes in strength measures, a: maximum grip force, b: max. rate of grip force development, and c: back-leg strength in experimental and control groups following the intervention

Unilateral Flexibility: Figure 4a shows the pre-test and post-test flexibility values for the right and left hands of the experimental and control groups. The statistical analysis of the three interaction mixed-model ANOVA found a significant difference between the groups (experimental - control) x tests (pre-test - post-test), $F(1, 18)=38.29, p<0.05$. According to the Tukey HSD analysis, a significant difference was found only between the pre-test (Mean= 20.31 ± 4.77 cm) and post-test (Mean= 26.27 ± 4.51 cm) values of the experimental group (Figure 4a).

Bilateral Flexibility: In the statistical analysis of the bilateral flexibility variable, 2 interactive mixed model ANOVA

statistical analysis method was used. As a result of the analysis, a significant difference was found between groups (experimental - control) x tests (pre-test - post-test), $F(1, 18)=25.33, p<0.05$. There was no difference between the pre-test values of the experimental and control groups. According to the Tukey HSD analysis, it was understood that the bilateral flexibility post-test values of the experimental group (Mean= 25.2 ± 4.11 cm) were found to be statistically significantly different from its own pre-test values (Mean= 17.35 ± 5.70 cm) and from both the pre-test (Mean= 18.25 ± 6.21 cm) and post-test (Mean= 19.1 ± 4.75 cm) values of the control group (Figure 4b).

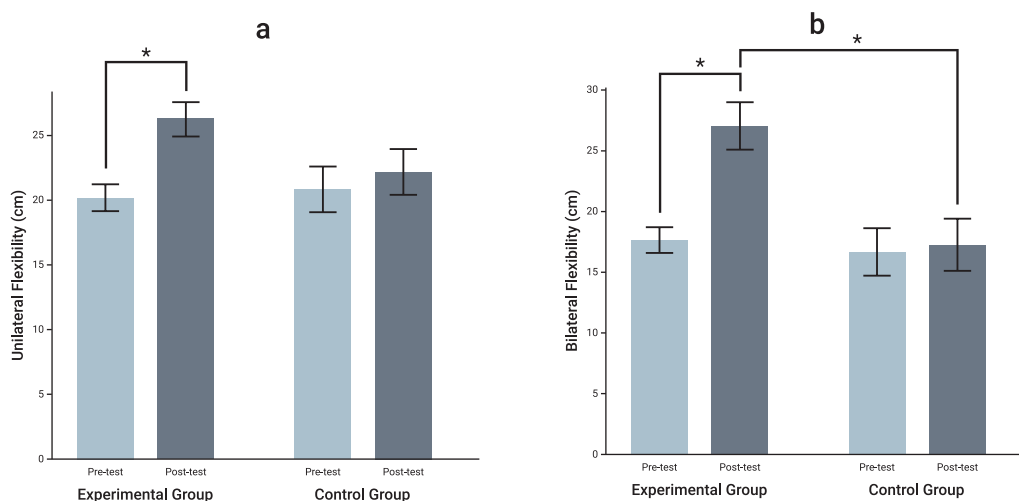


Figure 4. Changes in flexibility measures, a: unilateral flexibility and b: bilateral flexibility in experimental and control groups following the intervention.

Discussion

The aim of this study was to determine the effect of a 12-week adaptive horseback riding intervention on specific parameters in children with Cerebral Palsy (CP) classified as GMFCS Levels II and III. Our findings indicate that the

intervention significantly improved several core physical and motor competencies in the Experimental Group (EG).

In terms of the accuracy parameter, the post-test values of the Experimental Group (EG) after the intervention showed a statistically significant increase compared to both

their pre-test values and the post-test values of the Control Group (CG) ($p < 0.05$). This suggests that adaptive riding improves hand-eye coordination and hand stabilization skills, which are critical for the development of gross and fine motor skills in children with CP. Additionally, numerous studies have demonstrated that adaptive riding enhances hand-eye coordination, a crucial element in the development of gross and fine motor skills in children with CP (Angsupaisal, 2015; Champagne, Corriveau & Dugas, 2017; Stergiou et al., 2017; Stergiou et al., 2023). However, there are also studies reporting that horseback riding-based exercise does not affect gross motor function in people with cerebral palsy (Alemdaroğlu et al., 2016; Davis et al., 2009). According to our assessment, most of the studies that yielded such results may be related to the wide age range of the subject groups and the different levels and types of affected, the duration and content of the intervention, and especially the fact that the interventions were mostly interventions other than adapted horse riding (such as hippotherapy).

Unlike the accuracy parameter, no significant difference was found between the EG and CG groups in the linearity tests. While a relative improvement in left-hand performance was noted in the EG group, this difference did not reach statistical significance. Based on this result, we believe that the 12-week period may not be sufficient and that longer-term studies or further research with different age groups is warranted.

The intervention produced significant increases in Maximum Grip Force (MGF) and Rate of Grip Force Development (RGFD) in the experimental group (EG) ($p < 0.05$), while no changes were observed in the control group (CG). These results align with previous literature indicating that horseback riding therapy enhances grip strength (Žalienė et al., 2018). A number of studies have underscored the significance of the temporal characteristics of force production as a crucial indicator of health (Aleknavičiūtė-Ablomkė, Savenkovas, Mockevičius, & Miliūnas, 2015) and functionality in daily living (Heyn et al., 2023). Consequently, the enhancement in RGFD values in our experimental group is particularly noteworthy and merits further investigation in subsequent studies.

A substantial enhancement in back and leg strength was observed in the EG group ($p < 0.05$). This finding aligns with research indicating that adaptive riding activities enhance lower body strength in children and older adults (Moreau, Falvo, & Damiano, 2012; Scholtes et al., 2010). The observed improvements were attributed to repetitive, moderate-intensity, half-squat-like movements (stirrup stand-ups and controlled crunches) performed in sets and repetitions throughout the sessions. This method bears partial similarity to lower extremity strength exercises recommended for CP (de Araújo et al., 2013; Merino-Andres, Garcia de Mateos-Lopez, Damiano, & Sanchez-Sierra, 2022; Mockford & Caulton, 2008; Ross, MacDonald & Bigouette, 2016) providing a distinctive strengthening technique.

Strengths of the study

This study demonstrates several methodological and conceptual strengths. First, the adaptive riding intervention was individually planned and systematically implemented

over a 12-week period, ensuring consistency and adherence to the intervention protocol. Second, the program integrated functional lower extremity strengthening movements within a dynamic postural control environment, which differs from conventional ground-based strength exercises commonly used in rehabilitation for children with cerebral palsy. This approach may provide an alternative means of simultaneously targeting strength, balance, and coordination.

Additionally, the use of objective, instrument-based outcome measures allowed for precise assessment of changes in motor performance. Finally, the inclusion of a control group that continued standard rehabilitation programs strengthens the internal validity of the findings by enabling a clearer attribution of observed effects to the adaptive riding intervention.

Limitations

This study was limited to a small sample size of 20 children (both girls and boys) aged 8-12 years, all diagnosed with mild intellectual disability and cerebral palsy. The focus was on evaluating specific outcomes, including arm extension performance, maximum GF, maximum RGFD, flexibility, and back-leg strength parameters. In addition, the intervention program was limited to a 12-week period and 36 sessions for each child.

Conclusion

In conclusion, based on the aforementioned findings, analyses, conclusions, and evaluations, it can be concluded that 12 weeks of adaptive riding exercise has a positive impact on the development of hand-eye coordination, increased precision in upper extremity movements, increased strength in the lower extremities and hands, increased rate of grip force development, and improved flexibility in children with cerebral palsy (CP). A growing body of evidence demonstrates the positive impact of adaptive riding exercise on children with CP. It is noteworthy that adaptive riding activities offer a unique opportunity to implement a multimodal program that simultaneously trains single- or multi-joint motor skills such as flexibility, strength, and coordination. Because improvements in these parameters are hypothesized to contribute to independence in activities of daily living, adaptive riding exercises are recommended for inclusion in rehabilitation programs for individuals with cerebral palsy.

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Conflict of interest

No potential conflict of interest was reported by the authors.

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Effects of a Combined Iyengar Yoga and Yoga Nidra Intervention on Pain, Physiological, and Psychological Outcomes in Older Men with Chronic Low Back Pain: A Randomized Controlled Trial

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Abstract

Chronic low back pain (CLBP) is a leading cause of disability worldwide, particularly affecting older adults. Mind-body interventions show promise for pain management, but evidence for comprehensive yoga programs specifically targeting older men remains limited. The aim of the study was to assess the effects of a 3-month combined Iyengar yoga and Yoga Nidra (IY+YN) intervention on pain and associated outcomes in older men with chronic low back pain (CLBP). In this randomised controlled study (RCT) conducted in Dhenkanal, Odisha, India, we enrolled 60 men aged 55–65 years with CLBP lasting ≥ 3 months and pain intensity ≥ 4 on a 10-point Visual Analog Scale (VAS). Between Jan–Mar 2024, 55 participants were randomized (intervention $n=28$; control $n=27$) to either a 3-month IY+YN intervention (three 60-min yoga sessions plus 20–30 min YN weekly) or standard care (prescribed pain management and physical therapy). Primary outcome was change in pain intensity (VAS) at 3 months. Secondary outcomes included lumbar ROM, systolic BP, attention (Stroop test), anxiety (Beck Anxiety Inventory), and QoL (SF-36). Assessments were conducted at baseline, 6 weeks, and 3 months by blinded assessors. At 3 months, the intervention group showed significantly greater pain reduction compared with controls (mean diff. -2.6, 95% CI -3.3 to -1.9; $p<0.001$). Improvements were also seen in lumbar flexion (mean diff. 8.3° , $p<0.001$), systolic BP (mean diff. -7.5 mmHg, $p<0.001$), Stroop score (mean diff. -8.3

sec, $p < 0.001$), anxiety (mean diff. -8.7 , $p < 0.001$), and SF-36 physical and mental scores. Five minor adverse events were reported, resolving within 48 hours. In conclusion, a 3-month combined IY+YN significantly reduced pain and improved physical, psychological, and quality-of-life outcomes in older men with chronic low back pain. The program was safe and well tolerated, supporting its use as an effective adjunct to standard care.

Keywords: *yoga, relaxation, back pain, range of motion, quality of life*

Introduction

Chronic low back pain (LBP) represents one of the leading causes of disability worldwide, affecting approximately 7.5% of the global population and imposing substantial economic and healthcare burdens (Safiri et al., 2023). The prevalence of chronic LBP increases with age, particularly among men in their sixth and seventh decades of life, with epidemiological studies indicating that up to 40% of men aged 55-65 years experience persistent low back symptoms (Lo et al., 2021). Despite the significant impact of this condition, conventional treatment approaches including pharmacotherapy, physical therapy, and surgical interventions often provide suboptimal outcomes, with a substantial proportion of patients reporting persistent pain and disability (Alperovitch-Najenson et al., 2023).

The multidimensional nature of chronic LBP, encompassing physical, psychological, and neurophysiological components, suggests the need for integrative approaches that address these interconnected aspects simultaneously (Shi & Wu, 2023). Mind-body interventions have gained increasing attention in recent years as potentially valuable complements or alternatives to conventional treatment modalities (Islam et al., 2022; Maheshkumar et al., 2022). Among these interventions, yoga has shown promise in managing chronic pain conditions, with systematic reviews suggesting moderate evidence for its effectiveness in reducing pain intensity and improving function in patients with chronic LBP (Mann, 2024).

Iyengar yoga, a form of Hatha yoga distinguished by its emphasis on precise anatomical alignment, detailed instructions, and the use of props to support proper positioning, may be particularly suitable for individuals with chronic LBP (Amin & Goodman, 2014). The methodical approach of Iyengar yoga allows for modifications tailored to individual limitations and has demonstrated efficacy in improving pain, disability, and quality of life in mixed-gender populations with chronic LBP (Shapiro & Cline, 2004). However, most studies have included predominantly female participants, leaving uncertainty about the effectiveness of this approach specifically for men, who may present with different pain patterns, biomechanical factors, and psychological responses to pain.

Yoga Nidra, a systematic form of guided meditation that induces deep relaxation while maintaining awareness, represents another promising approach for life style management (Vanitha et al., 2018). This practice has been associated with reduced sympathetic activation, improved stress response, and modulation of pain perception through enhanced interoceptive awareness (Ragavee et al., 2024). Preliminary studies suggest that Yoga Nidra may complement physical yoga

practices by addressing psychological dimensions of chronic pain, including anxiety, catastrophizing, and pain-related fear, which are recognized as important factors in pain chronicity (Moszeik et al., 2022).

Despite the potential synergistic benefits of combining physical yoga practice with meditation techniques, few studies have evaluated integrated approaches specifically targeting older men with chronic LBP. This population may face unique challenges related to pain perception, body awareness, and adherence to mind-body interventions that have traditionally attracted predominantly female participants (Nikolis et al., 2024). A meta-analysis by Anheyar et al. (2022) of 29 randomized trials ($n=2,702$) found moderate effects on function (SMD -0.48) and pain (SMD -0.40) at 3-6 months, but noted considerable heterogeneity ($I^2=64-79%$) across studies. Tilbrook et al. (2011) demonstrated 2.2-point improvement in disability scores among 313 adults, but their sample was 71% female with mean age 47 years. Chang et al. (2016) demonstrated in a 12-week trial among 150 adults with chronic LBP that Hatha yoga practice reduced pain scores from 6.8 ± 1.2 to 3.4 ± 1.5 on a 0-10 visual analog scale, with improvements persisting at 6-month follow-up, though their sample included only 28% male participants. Critically, these studies have predominantly enrolled middle-aged women, typically excluded individuals with significant disability, and rarely examined Iyengar yoga specifically among older men, representing a notable evidence gap.

The present study addresses these gaps by evaluating the effects of a structured program combining Iyengar yoga and Yoga Nidra on pain intensity, functional mobility, autonomic function, cognitive attention, anxiety, and quality of life in men aged 55-65 years with chronic LBP. By focusing on this specific demographic and employing rigorous methodology, this research aims to provide evidence for an integrative approach that may more comprehensively address the complex nature of chronic LBP in a population with significant unmet treatment needs.

Methods

Participant characteristics

Between January and March 2024, 87 men with chronic low back pain were assessed for eligibility, of whom 60 met the inclusion criteria and were randomly assigned to either the intervention group ($n=30$) or the control group ($n=30$). Five participants (two from the intervention group, three from the control group) withdrew from the study, resulting in 55 participants (28 intervention, 27 control) completing the 3-month protocol (Figure 1B).

Study design

This study was conducted as a prospective, randomized, parallel-group, controlled trial with a 1:1 allocation ratio. Participants were randomly assigned to either the intervention group (Iyengar yoga combined with Yoga Nidra) or the control group (standard care) using computer-generated random numbers. The study followed the Consolidated Standards of Reporting Trials (CONSORT) guidelines.

Ethics and dissemination

This study was approved by Meenakshi Medical College Hospital & Research Institute (approval number: MAHER/IEC/PhD/36/Nov24). Written informed consent was obtained from all participants.

Sample size determination

Sample size calculation was based on detecting a clinically significant difference in VAS pain scores between groups (Williams et al., 2009). Assuming a medium effect size (Cohen's d=0.5), 80% power, a two-sided alpha of 0.05, and an anticipated attrition rate of 15%, we calculated a required sample size of 60 participants (30 per group). This calculation was performed using G*Power software version 3.1.

Setting

The study was conducted at Saundarya (NGO) in Dhenkanal, Odisha, India from 3rd January 2025 to 3rd April 2025. All yoga sessions were conducted in a standardized environment under the supervision of certified yoga instructors.

Participants eligibility criteria

Eligible participants were men aged fifty-five to sixty-five years with CLBP persisting for at least three months. Additional inclusion criteria required self-reported pain intensity of four or greater on a ten-point Visual Analog Scale (VAS) at baseline, ability to attend regular Iyengar yoga and Yoga Nidra sessions over a three-month period, medical clearance to participate in moderate physical activity, and capacity to provide written informed consent.

We excluded men with history of psychosis, depression, mania, or brain damage, as well as those with history of suicidal ideation or significant aggression and violence. Additional exclusion criteria included active clinically significant disorder or disease requiring surgical intervention, prior lumbar surgery, presence of neurological deficit, history of spinal operation, vertebral fracture or dislocation, presence of any tumor causing varicose veins, blood clotting disorders, and current use of prolonged anticoagulant medication

Randomization and blinding

Randomization was performed using a computer-generated random number sequence created by a statistician not involved in participant recruitment or assessment. Allocation concealment was maintained using sequentially numbered, opaque, sealed envelopes. Due to the nature of the intervention, participants and yoga instructors could not be blinded; however, outcome assessors and data analysts were blinded to group assignment.

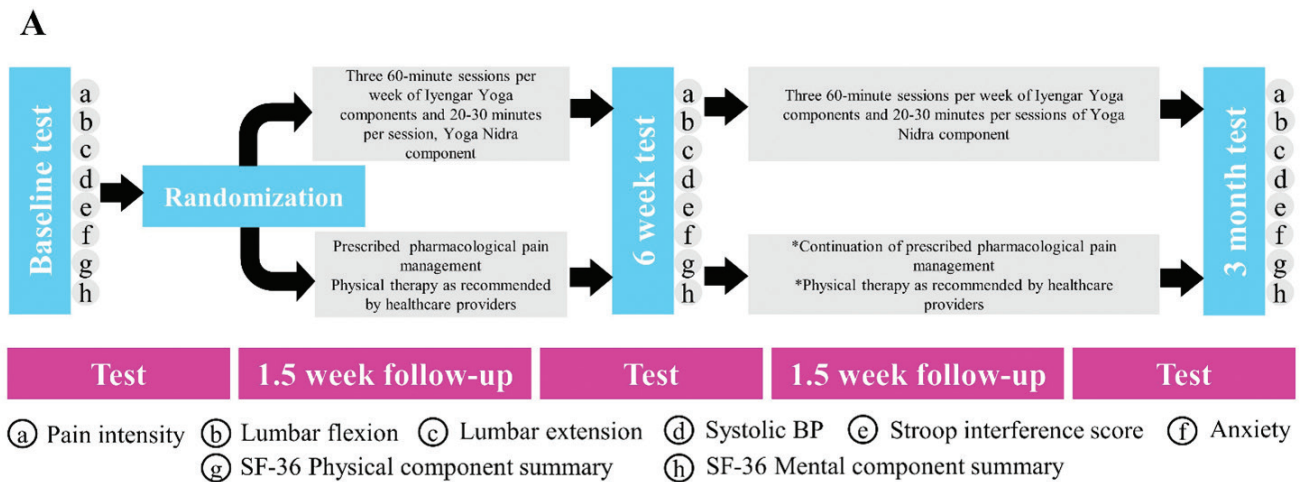
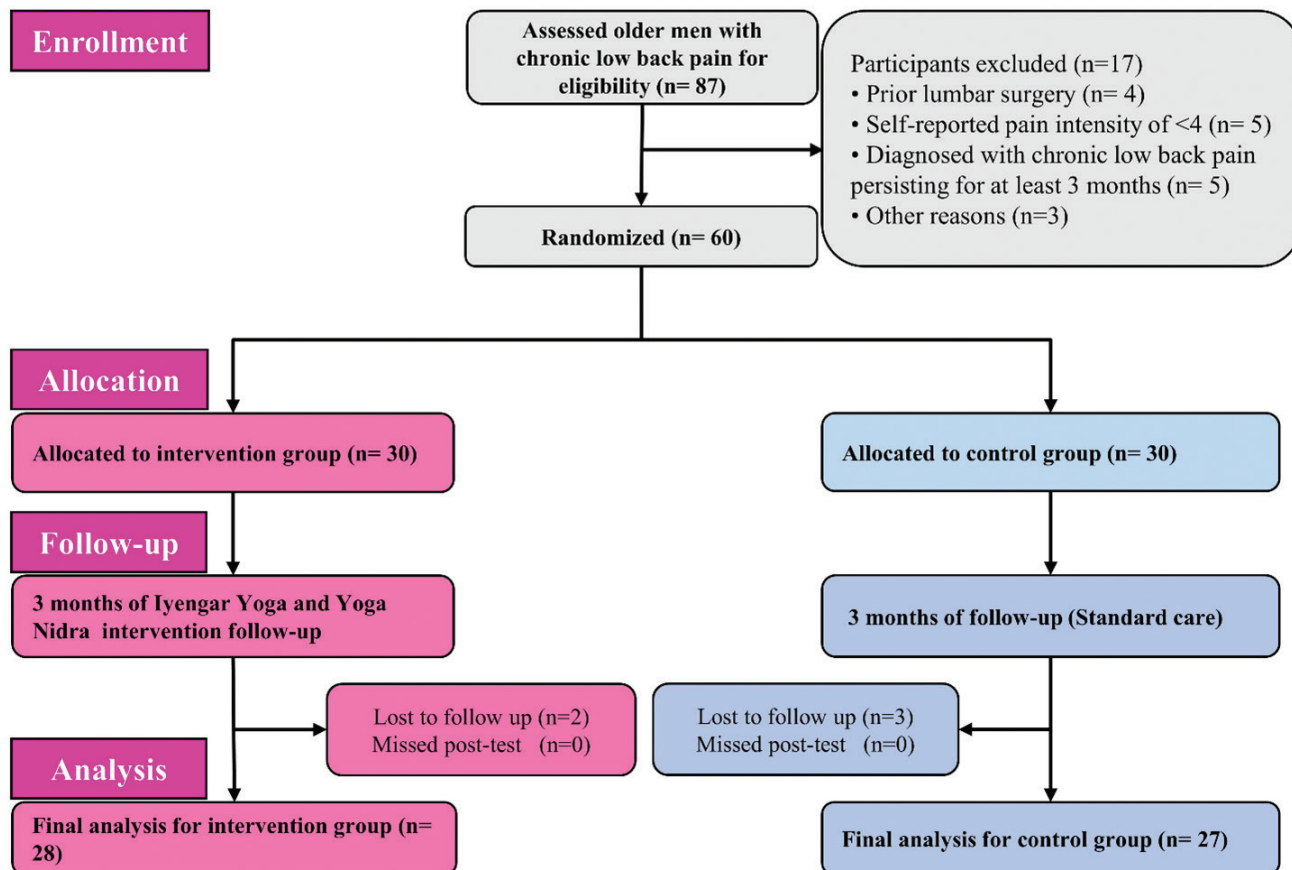


Figure 1. (A) Semantic representation of research study, (B) Consort flow chart. Interventions

B



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Figure 1. (A) Semantic representation of research study, (B) Consort flow chart. Interventions

Intervention group

Participants received a 3-month combined Iyengar yoga and Yoga Nidra program. The intervention comprised three weekly sixty-minute group sessions of Iyengar yoga led by certified instructors. Sessions followed structured sequences incorporating nine poses (Adhomukha Svanasana, Uttanasana, Viparita Dandasana, Marichyasana, Parsva Virasana, Supta Padangusthasana, Setubandha Sarvangasana, Viparita Karani, and Savasana) with props including blocks, straps, and bolsters to accommodate individual limitations. Poses were introduced progressively with modifications as needed. Each session integrated twenty to thirty minutes of Yoga Nidra using standardized audio-recorded instructions focusing on body awareness, breath regulation, and visualization. Participants received illustrated handouts and audio recordings to support daily fifteen to twenty minute home practice, with adherence tracked through practice logs.

Control group

Control participants continued standard care including prescribed pharmacological management and recommended physical therapy, with no yoga or meditation inter-

ventions during the study period. Monthly telephone calls maintained engagement.

Outcome measures

All assessments were conducted at baseline, 6 weeks, and 3 months by trained assessors blinded to group assignment. Standardized testing protocols were followed for each measure to ensure reliability and validity of the data collected. Semantic representation of this study was presented in figure 1 A.

Primary outcome

Pain Intensity: Pain was measured using the Visual Analog Scale (VAS), a widely validated instrument for pain assessment (Begum & Hossain, 2019). Participants marked their perceived pain level on a 100mm horizontal line anchored with “no pain” (0) and “worst pain imaginable” (10). The distance in millimeters from the “no pain” anchor to the participant’s mark was measured and converted to a 0-10 scale. Higher scores indicated greater pain intensity, with a reduction of ≥1.5 points or 30% from baseline considered clinically significant. Participants completed the VAS independently at each assessment timepoint, rating both their current pain and

average pain experienced over the previous week (Begum & Hossain, 2019).

Secondary outcomes

Range of Motion (ROM) of the Lumbar Spine: Lumbar spine mobility was assessed using the dual inclinometer method (MIE Medical Research Ltd, model J-Tech) following American Medical Association guidelines (MacDermid et al., 2014). Measurements were taken for flexion (normal range 0-60 degrees), extension (normal range 0-25 degrees), and lateral flexion (normal range 0-25 degrees bilaterally). Three measurements were taken for each movement, and the average was recorded. Improvements of ≥ 5 degrees in any direction were considered clinically meaningful. All measurements were performed by the same trained physical therapist to minimize inter-rater variability.

Systolic blood pressure: Blood pressure was measured using an automated oscillometric device (Omron HEM-7320-LA) following American Heart Association protocols. Participants were seated quietly for at least 5 minutes before measurement, with the arm supported at heart level. Three consecutive readings were taken at 1-minute intervals, and the average of the last two readings was recorded. Measurements were taken at the same time of day for each assessment period to control for diurnal variations. A reduction of ≥ 5 mmHg in systolic blood pressure was considered clinically significant.

Attention: Cognitive attention was assessed using the Stroop Color and Word Test, a neuropsychological assessment that measures selective attention, cognitive flexibility, and processing speed (Scarpina & Tagini, 2017). The test consisted of three trials: word reading, color naming, and color-word interference. The time to complete each trial and number of errors were recorded. The interference score was calculated as the difference between the time taken for the interference trial and the predicted color naming time. Lower scores indicated better selective attention and cognitive control. Age-adjusted norms were used for interpretation (Begum & Hossain, 2019).

Anxiety levels: Anxiety was measured using the Beck Anxiety Inventory (BAI), a 21-item self-report questionnaire (Fydrich et al., 1992). Participants rated how much they had been bothered by each symptom over the past week on a 4-point scale ranging from 0 (not at all) to 3 (severely, I could barely stand it). Total scores ranged from 0-63, with 0-7 indicating minimal anxiety, 8-15 mild anxiety, 16-25 moderate anxiety, and 26-63 severe anxiety. A reduction of ≥ 7 points from baseline was considered clinically significant. The BAI has demonstrated high internal consistency ($\alpha=0.92$) and

test-retest reliability ($r=0.75$) in previous studies with similar populations.

Health-related Quality of Life: Quality of life was assessed using the SF-36 Health Survey, a multi-purpose health survey consisting of 36 questions (Hays et al., 2002). The SF-36 yields an 8-scale profile of functional health and well-being scores (physical functioning, role limitations due to physical health, role limitations due to emotional problems, energy/fatigue, emotional well-being, social functioning, pain, and general health) as well as physical and mental health summary components. Each scale is directly transformed into a 0-100 scale, with higher scores indicating better health status. A change of ≥ 5 points in any domain or ≥ 3 points in summary measures was considered clinically meaningful. The SF-36 has been extensively validated in chronic pain populations with excellent psychometric properties.

Statistical analysis

All statistical analyses were conducted using SPSS software version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables were presented as mean \pm standard deviation (SD). Baseline characteristics were compared between groups using independent t-tests for continuous variables and chi-square tests for categorical variables.

The primary analysis employed mixed-model analysis of variance (ANOVA) with repeated measures to examine the effects of the intervention on outcome variables across the three assessment points (baseline, 6 weeks, and 3 months). The mixed-model included group (intervention vs. control) as the between-subjects factor and time (baseline, 6 weeks, 3 months) as the within-subjects factor. The primary hypothesis test focused on the group \times time interaction, which indicates whether changes over time differed between groups. When significant interactions were detected, post-hoc pairwise comparisons with Bonferroni correction were conducted to identify specific time points at which groups differed. Effect sizes were calculated as partial eta-squared (η^2) for ANOVA main effects and interactions, with values of 0.01, 0.06, and 0.14 interpreted as small, medium, and large effects, respectively. For post-hoc comparisons, Cohen's *d* was calculated using pooled standard deviations. Statistical significance was set at two-tailed $\alpha=0.05$ for all analyses.

Results

Baseline demographic and clinical characteristics were similar between groups (Table 1).

Table 1. Baseline characteristics of study participants

Characteristic	Intervention group (n=30)	Control group (n=30)
Demographics		
Age (years)	59.3 (4.7)	60.1 (4.3)
BMI (kg/m ²)	27.2 (3.8)	26.8 (4.1)
Education (years)	13.6 (3.5)	13.2 (3.7)

Table 1. Baseline characteristics of study participants

Characteristic	Intervention group (n=30)	Control group (n=30)
Pain characteristics		
Duration of low back pain (months)	42.5 (28.3)	45.2 (30.1)
Pain intensity (VAS 0-10)	6.8 (1.3)	6.7 (1.4)
Clinical measures		
Lumbar flexion ROM (degrees)	32.1 (9.7)	31.8 (9.3)
Lumbar extension ROM (degrees)	12.6 (4.3)	12.3 (4.5)
Systolic BP (mm Hg)	142.3 (12.7)	143.1 (13.2)
Diastolic BP (mm Hg)	86.8 (7.9)	87.3 (8.1)
Psychological measures		
Anxiety (BAI 0-63)	18.7 (8.5)	19.1 (8.2)
Health status		
SF-36 Physical component summary	36.4 (7.3)	35.9 (7.5)
SF-36 Mental component summary	42.1 (8.6)	41.8 (8.4)
Current treatments		
Pain medication use, n (%)	24 (80.0)	25 (83.3)
NSAIDs	18 (60.0)	19 (63.3)
Acetaminophen	16 (53.3)	17 (56.7)
Muscle relaxants	8 (26.7)	7 (23.3)
Opioids	5 (16.7)	6 (20.0)
Prior treatments, n (%)		
Physical therapy	22 (73.3)	23 (76.7)
Chiropractic care	11 (36.7)	12 (40.0)
Massage therapy	13 (43.3)	15 (50.0)
Acupuncture	7 (23.3)	6 (20.0)
Comorbidities, n (%)		
Hypertension	16 (53.3)	17 (56.7)
Type 2 diabetes	8 (26.7)	7 (23.3)
Osteoarthritis	11 (36.7)	12 (40.0)
Sleep disorders	14 (46.7)	13 (43.3)

Note. Data are mean (SD) unless specified otherwise. BMI=Body Mass Index. VAS=Visual Analog Scale. ROM=Range of Motion. BP=Blood Pressure. BAI=Beck Anxiety Inventory. SF-36=36-Item Short Form Health Survey. NSAIDs=Non-steroidal Anti-inflammatory Drugs

Primary outcome

Mixed-model ANOVA revealed a significant group \times time interaction for pain intensity measured by the Visual Analog Scale ($F(2,106)=28.45$, $p<0.001$, $\eta^2=0.35$), indicating that changes in pain over the three-month period differed significantly between groups. The main effect of time was significant ($F(2,106)=47.23$, $p<0.001$, $\eta^2=0.47$), as was the main effect of group ($F(1,53)=32.18$, $p<0.001$, $\eta^2=0.38$).

Post-hoc pairwise comparisons with Bonferroni correction revealed that the intervention group showed significantly greater pain reduction than the control group at 6 weeks (mean

difference -1.8 points difference, 95% CI: -2.4 to -1.2; $p<0.001$, Cohen's $d=1.12$) and at 3 months (mean difference -2.6 points, 95% CI: -3.3 to -1.9; $p<0.001$, Cohen's $d=1.68$). Within-group analyses showed that the intervention group experienced significant pain reduction from baseline to 6 weeks (mean change -2.5 points, $p<0.001$) and from 6 weeks to 3 months (mean change -1.6 points, $p<0.001$), whereas the control group showed only modest reduction from baseline to 6 weeks (mean change -0.8 points, $p=0.012$) with no further change from 6 weeks to 3 months (mean change -0.6 points, $p=0.098$).

The proportion of participants achieving clinically mean-

ingful pain reduction ($\geq 30\%$ from baseline) at 3 months was significantly higher in the intervention group (23 [82.1%] of 28) than in the control group (7 [25.9%] of 27; $\chi^2=17.42$, $p<0.001$).

Secondary outcomes

Range of motion: Mixed-model ANOVA demonstrated significant group \times time interactions for both lumbar flexion ($F(2,106)=18.67$, $p<0.001$, $\eta^2=0.26$) and lumbar extension ($F(2,106)=12.34$, $p<0.001$, $\eta^2=0.19$). Post-hoc comparisons at 3 months showed the intervention group had significantly greater improvements in flexion (mean difference 8.3° , 95% CI: 5.9 to 10.7; $p<0.001$, Cohen's $d=0.91$) and extension (mean difference 4.2° , 95% CI: 2.8 to 5.6; $p<0.001$, Cohen's $d=0.94$) compared with the control group.

Systolic blood pressure: The group \times time interaction was significant ($F(2,106)=9.87$, $p<0.001$, $\eta^2=0.16$), with the intervention group showing significantly greater reduction at 3 months (mean difference -7.5 mm Hg, 95% CI -10.8 to -4.2 ;

$p<0.001$, Cohen's $d=0.69$).

Attention: Stroop Color and Word Test interference scores showed a significant group \times time interaction ($F(2,106)=8.45$, $p<0.001$, $\eta^2=0.14$), with the intervention group demonstrating greater improvement at 3 months (mean difference -8.3 seconds, 95% CI: -12.1 to -4.5 ; $p<0.001$, Cohen's $d=0.64$).

Anxiety: Beck Anxiety Inventory scores demonstrated a significant group \times time interaction ($F(2,106)=15.23$, $p<0.001$, $\eta^2=0.22$), with significantly greater reduction in the intervention group at 3 months (mean difference -8.7 points, 95% CI: -11.4 to -6.0 ; $p<0.001$, Cohen's $d=1.21$).

Quality of life: SF-36 showed significant group \times time interactions for both physical component summary ($F(2,106)=11.76$, $p<0.001$, $\eta^2=0.18$; 3-month difference 6.4 points, 95% CI 4.2 to 8.6; $p<0.001$, Cohen's $d=0.82$) and mental component summary ($F(2,106)=9.34$, $p<0.001$, $\eta^2=0.15$; 3-month difference 5.8 points, 95% CI 3.7 to 7.9; $p<0.001$, Cohen's $d=0.71$).

Table 2. Primary and secondary outcomes at baseline, 6 weeks, and 3 months

Outcome	Time	Intervention (n=28) Mean (SD)	Control (n=27) Mean (SD)	Group \times Time ANOVA F, p, η^2	3-Month Mean Difference (95% CI)	p	Cohen's d
Pain intensity (VAS)	Baseline	6.8 (1.3)	6.7 (1.4)				
	6 weeks	4.3 (1.6)	5.9 (1.5)	$F(2,106)=28.45$			
	3 months	2.7 (1.4)	5.3 (1.7)	$p<0.001$, $\eta^2=0.35$	-2.6 (-3.3 to -1.9)	<0.001	1.68
Lumbar flexion ($^\circ$)	Baseline	32.1 (9.7)	31.8 (9.3)				
	6 weeks	38.4 (10.2)	34.7 (9.5)	$F(2,106)=18.67$			
	3 months	45.8 (9.6)	37.5 (9.9)	$p<0.001$, $\eta^2=0.26$	8.3 (5.9 to 10.7)	<0.001	0.91
Lumbar extension ($^\circ$)	Baseline	12.6 (4.3)	12.3 (4.5)				
	6 weeks	15.8 (4.7)	13.6 (4.4)	$F(2,106)=12.34$			
	3 months	18.7 (4.5)	14.5 (4.8)	$p<0.001$, $\eta^2=0.19$	4.2 (2.8 to 5.6)	<0.001	0.94
Systolic BP (mmHg)	Baseline	142.3 (12.7)	143.1 (13.2)				
	6 weeks	136.5 (11.8)	141.2 (12.4)	$F(2,106)=9.87$			
	3 months	132.4 (10.6)	139.9 (11.7)	$p<0.001$, $\eta^2=0.16$	-7.5 (-10.8 to -4.2)	<0.001	0.69
Stroop interference (s)	Baseline	42.6 (15.3)	41.9 (14.7)				
	6 weeks	36.2 (14.1)	39.5 (14.2)	$F(2,106)=8.45$			
	3 months	30.4 (12.8)	38.7 (13.4)	$p<0.001$, $\eta^2=0.14$	-8.3 (-12.1 to -4.5)	<0.001	0.64
Anxiety (BAI)	Baseline	18.7 (8.5)	19.1 (8.2)				
	6 weeks	12.6 (7.4)	16.8 (7.8)	$F(2,106)=15.23$			
	3 months	8.2 (6.3)	16.9 (7.6)	$p<0.001$, $\eta^2=0.22$	-8.7 (-11.4 to -6.0)	<0.001	1.21
SF-36 Physical	Baseline	36.4 (7.3)	35.9 (7.5)				
	6 weeks	41.7 (7.8)	38.1 (7.6)	$F(2,106)=11.76$			
	3 months	46.2 (8.1)	39.8 (7.9)	$p<0.001$, $\eta^2=0.18$	6.4 (4.2 to 8.6)	<0.001	0.82
SF-36 Mental	Baseline	42.1 (8.6)	41.8 (8.4)				
	6 weeks	46.3 (8.2)	43.5 (8.3)	$F(2,106)=9.34$			
	3 months	50.7 (7.8)	44.9 (8.5)	$p<0.001$, $\eta^2=0.15$	5.8 (3.7 to 7.9)	<0.001	0.71

Note. Mixed-model ANOVA tested group \times time interaction. All interactions were significant ($p<0.001$), indicating greater improvement in the intervention group compared with controls. Post-hoc comparisons at 3 months were Bonferroni-corrected. η^2 = partial eta-squared; d = Cohen's d

Adherence and Adverse Events

Adherence to the yoga intervention was high, with participants attending a mean of 31.4 (SD 4.8) of 36 sessions (87.2%). Home practice adherence, defined as completing at least 15 minutes of the prescribed exercises, was reported on a mean of 68.3 (SD 14.7) of 90 days (75.9%).

Five minor adverse events were reported in the intervention group (muscle soreness [n=3] and temporary increase in back pain [n=2]), all of which resolved within 48 hours without need for additional medical attention. No serious adverse events were recorded in either group.

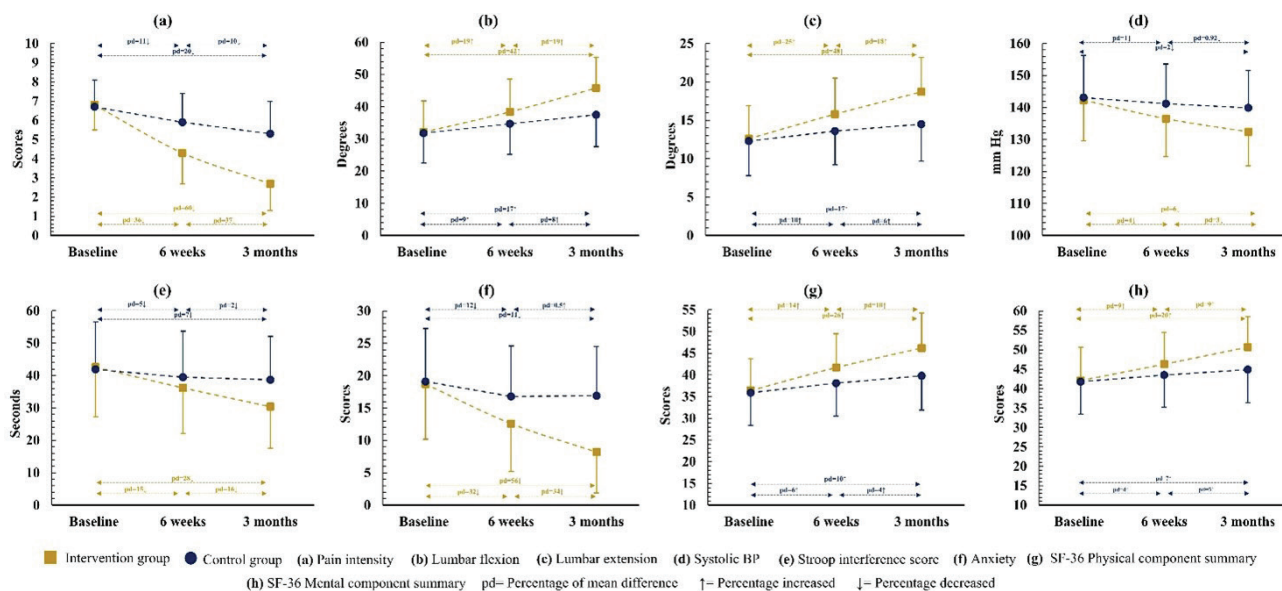


Figure 2. Means and percentage differences in the intervention and control groups of primary and secondary outcome measures between three tests

Discussion

In this randomized clinical trial, a 3-month program combining Iyengar yoga and Yoga Nidra significantly reduced pain intensity, improved lumbar spine mobility, decreased systolic blood pressure and anxiety levels, enhanced attention, and improved health-related quality of life in men aged 55-65 years with chronic low back pain compared with standard care. The magnitude of these improvements was both statistically significant and clinically meaningful.

The substantial reduction in pain intensity observed in this study (mean difference of 2.6 points on the VAS at 3 months) exceeds the commonly accepted threshold for clinically significant improvement in chronic pain (1.5 points or 30% reduction). This finding aligns with previous research on yoga interventions for chronic low back pain, although the effect size in our study appears larger than those reported in meta-analyses of conventional yoga programs (typically 0.5-1.5 points on comparable scales) (Cramer et al., 2017; Holtzman & Beggs, 2013; Zhu et al., 2020).

The improvements in range of motion were similarly noteworthy. The mean increase of 8.3° in lumbar flexion exceeds the minimal clinically important difference of 5° (Parker et al., 2012) suggesting functional benefits that could translate to improved activities of daily living for these men. Previous studies have demonstrated modest improvements in spinal mobility with yoga practice (Neyaz et al., 2019; Tankha et al., 2024), but few have specifically quantified changes using standardized dual inclinometer measurements in older men (Dabhi, 2023).

The observed reduction in systolic blood pressure (mean difference of 7.5 mmHg) is consistent with previous research on mind-body interventions for hypertension and represents a clinically meaningful change that could reduce cardiovascular risk in this population (Wankhar et al., 2024; Yang et al., 2021). This finding is particularly relevant as hypertension frequently co-exists with chronic pain in older adults and may share underlying pathophysiological mechanisms related to autonomic dysfunction and systemic inflammation (Shobana et al., 2022; Thanalakshmi et al., 2020).

The improvements in cognitive attention, as measured by the Stroop test, suggest potential benefits beyond physical parameters. This finding adds to emerging evidence that yoga practices may enhance cognitive function in older adults (Jagadeesan et al., 2021), potentially through mechanisms including improved cerebral blood flow, reduced inflammation, and enhanced vagal tone (Abirami et al., 2024; Lalitha et al., 2021; Padmavathi et al., 2023).

The significant reduction in anxiety (mean difference of 8.7 points on the BAI) exceeds the established clinically meaningful threshold of 7 points and highlights the psychological benefits of this integrated approach. This is consistent with previous research demonstrating anxiolytic effects of both yoga and meditative practices (Padmavathi et al., 2023), though few studies have specifically addressed anxiety in men with chronic pain.

Quality of life improvements across both physical and mental domains of the SF-36 reflect the broad impact of the

intervention on overall well-being. The magnitude of these improvements (6.4 and 5.8 points for physical and mental component summaries, respectively) exceeds established thresholds for clinical significance (3 points) and suggests that benefits extend beyond symptom reduction to enhanced functional capacity and psychological well-being (Malarvizhi et al., 2019).

The high adherence rates observed in this study (87.2% for supervised sessions and 75.9% for home practice) are noteworthy, particularly given that men typically demonstrate lower participation rates in mind-body interventions. This suggests that the structured, physically engaging nature of Iyengar yoga, combined with the accessible, restorative qualities of Yoga Nidra, may appeal to this demographic. The low rate of minor adverse events supports the safety of this approach when properly implemented with appropriate modifications.

Strengths

Key strengths of this study include the use of blinded assessors for objective outcome measures including range of motion and blood pressure, reducing detection bias despite the inability to blind participants to intervention assignment. The comprehensive assessment battery spanning physical (pain, mobility), physiological (blood pressure), cognitive (attention), and psychological (anxiety, quality of life) domains provides a multidimensional evaluation of intervention effects in an understudied population of older men with chronic low back pain. The high retention and adherence rates (eighty-seven percent for supervised sessions and seventy-six percent for home practice) combined with standardized intervention delivery using audio-recorded Yoga Nidra instructions support both the feasibility and replicability of this integrated approach.

Limitations

The intervention combined sixty minutes of Iyengar yoga with twenty to thirty minutes of Yoga Nidra in each session, making it impossible to determine which component contributed most to observed outcomes, and the specific emphasis on nine therapeutic asanas limits extrapolation to other yoga styles. The control group received standard care with monthly telephone calls but no active intervention matched for the three supervised sessions weekly, preventing separation of specific intervention effects from nonspecific factors including instructor attention and group participation. We did not assess disability using condition-specific instruments such as the Roland-Morris Disability Questionnaire or Oswestry Disability Index, nor did we evaluate cost-effectiveness or collect qualitative data on participant experiences.

Conclusions

This study provides evidence that a combined Iyengar yoga and Yoga Nidra program is an effective intervention for reducing pain, improving physical function, and enhancing psychological well-being in middle-aged and older men with chronic low back pain. The substantial effects observed across

multiple domains suggest this approach may address the complex, multidimensional nature of chronic pain more comprehensively than conventional single-modality treatments. The high adherence rates and minimal adverse events, combined with clinical improvements, support the feasibility and safety of implementing this three-month program in clinical settings serving older men with chronic low back pain. These findings support the integration of structured yoga and meditation practices into comprehensive pain management programs for men with chronic low back pain.

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Conflicts of interest

The authors declare that there are no conflict of interest.

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Certain factors that inhibit the success of two- and three-point shots in basketball

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Abstract

The aim of this research was to examine whether there are significant differences in the success rate of two-point and three-point both shooting, without and under the influences of inhibiting factors such as fatigue and psychological stress, among basketball players with various levels of shooting accuracy within a team. The experiment involved two groups of participants (advanced and average), which included 18 senior players of the Basketball Club „Student“ from Bajina Bašta, all male, aged 16 to 35 years. The players performed shooting from five characteristic positions (for both two- and three-points shoots) under three different conditions: without inhibiting factors, under fatigue, and with defending players present. The participants were divided into two subsamples based on their two- and three-point shooting percentages from the previous season. The results obtained using a *Mixed between-within subject ANOVA* indicated a decreasing trend in shooting percentage under the influence of inhibiting factors, with a statistically significant decline for three-point shooting (statistically significant main situation effect $F=8.23$, $p=0.001$, with important effect $\eta^2=0.34$). The study highlights the need for further research with a large sample, additional situational parameters and biomechanical analysis of shooting technique under influencing factors. The results suggest an optimization of the training process by integrating situational shooting drills that include elements of fatigue and psychological stress.

Keywords: *basketball, accuracy, fatigue, psychological stress*

Introduction

Basketball is a game in which the rules determine the winning team as the one that scores a greater number of points, which is why the shooting percentage (two-point, three-point, and free throw attempts) is considered as one of the leading factors in deciding the winner of the basketball competitions (Chen et al., 2018). The most common way of scoring in basketball is the jump shot, which is seen as the most important element of the game due to its high demands for execution in situational context (Struzik et al., 2014). The importance of shooting in modern basketball is further supported by the comparative study of Wang and Zeng (2022), which analyzed shooting tendencies based on official NBA statistics across the 2010/2011 and 2020/2021 seasons. Their results indicate that alongside the increasing trend in the number of three-point attempts (from 22% to 39%) and decrease in two-point attempts (from 20% to 10%), the success rate of three-point shooting has also improved over the examined period. Ad-

ressing free-throw shooting performance from 1969. to 2019. in NBA competitions (2.6 million attempts sample size), authors (Morgulev et al., 2022) concluded that shooting efficiency fluctuates around 75%, and that free throws represent one of the most influential factors affecting the final game outcome. The analysis of parameters that influence the shooting efficiency of young players (age 16, 18 and 20) in European Championships from 2017 to 2022, authors (Rajković et al., 2025) indicated that shooting performance from perimeter positions (three-point shooting) and internal positions (two-point shooting) significantly affects the overall shooting efficiency index of basketball players.

The search for offense strategies in the strongest basketball league (NBA) and analysis of 10 seasons (2009-2019), showed that higher efficiency in three-point shooting increases the likelihood of winning, while two-point shooting has lesser impact on the final outcome (Gou & Zhang, 2022). Same study demonstrates that teams with higher percentages

of three-point shot attempts secure play-off positions, whereas lower-ranked teams tend to have a better two-point shooting percentage, suggesting that higher-ranked teams heighten the perimeter play, while lower-ranked teams rely more on inside scoring. These findings are consistent with studies examining basketball performance parameters during the Tokyo 2021 Olympic Games (Simović et al., 2022). Their results indicated that winning teams attempted more three-point range and had higher percentage of two-point and three-point shots, compared to losing teams, which represents three out of five most important basketball game parameters. These results are supported by research aiming to show the change of standards for two- and three-point shots and determine their influence on match outcome (Zajac et al., 2023). The results have shown that during the analyzed period the number of three-point attempts increased and two-point attempts decreased, and the success rate of three-point shots improved while two-point shots did not differ significantly. Forecasting the game outcome in the NBA regular seasons over three seasons from 2020 to 2023, based on statistical performance indicators in half-time analysis (both individual and team-based), some researchers concluded that key predictors of success include two- and three-point shooting percentages, as well as free-throw shooting efficiency (Tsagris et al., 2024).

As the results of most studies show that the success of two-point, three-point and free throw shootings are the key factors of winning in basketball competitions, a certain number of authors have dealt with potential factors that influence shooting percentages in situational conditions. A study that examined the relationship between cardiorespiratory markers (maximum oxygen consumption – VO₂ max and maximum heart rate per minute – HRmax), on the one hand, and shooting success for the three points, on the other hand, with 38 senior basketball players sample from three basketball levels in Greece (the shortest competitive experience of 6 years), showed that fatigue significantly affects the decrease in shooting efficiency due to changes in release angles, and the velocity increase of the shot (Bourdass et al., 2024). Pojskić et al. (2018), dealing with the influence of anaerobic capacity on shooting efficiency, as well as the relationship between field tests results and shooting performance in competitive situations with 38 senior basketball players sample from different levels from the territory Bosnia and Herzegovina, conclude that a higher level of anaerobic capacity impacts the success in dynamic shooting tests and that the test results show a high correlation with official competition statistics.

One of the inhibiting factors of performance in two-point shooting in situational conditions is psychological stress which most often arises due to the presence of a defensive player (opponent) in competitive situations. Numerous studies show that the presence of a defensive player affects changes in shooting technique (the player performing the jump shot hands the ball faster, release angles are reduced and the ball entry angles into the basket are changed), which reduces the execution performance (Kambič et al., 2022; Rojas et al., 2000). A study that examined the synergistic influence of fatigue and psychological stress on the kinematic structure of the jump shot on a sample of 14 participants members of university in

China, showed that these factors affect jump height, shot velocity, changes in the ball release, and reduce the three-point shooting percentage (Li et al., 2024). Despite the fact that the result of certain studies show that the shooting percentages for two- and three-points are higher without the presence of a defensive player (compared to the results with their presence), and the percentages vary depending on their distance (Amaro et al., 2022), the study (Morgulev, 2025) conducted on a larger sample of participants (members of the NBA league) contradicts the previously mentioned findings.

Although the listed studies deal with the problem of inhibitory factors on shooting success for two- and three-points (which is a crucial parameter of victory in competitions according to studies) there are few comparative studies based on the exact influence of interfering factors (e.g., fatigue and psychological stress) while executing dynamical shot. The aim of this study is to determine whether there are differences, and to what extent, in the success rate of two- and three-point shooting, with and without the presence of inhibitory factors such as psychological stress and fatigue, among players of various levels of accuracy, determined on the basis of statistical data from the official statistics of their previous games, as well as expert evaluations.

Method

Study design

The research was conducted on basketball players of senior team Basketball Club “Student” from Bajina Bašta, Serbia, which competes in the Second Regional League – West Region. Each participant was evaluated for shooting success in two- and three-point shots in different situations. The first situation involved performing a dynamic shot without disturbing factors; the second implied its execution after physical fatigue (caused by a motor task of anaerobic type directly previous to the shot); while in the third situation a psychological stress factor was included (whose source is the defensive player’s pressure shortening the time of performing a jump shot). Players were divided into two groups – advanced and average. This was based on the quality achieved in competitive matches during the previous season. The data recorded in different shooting situations were compared using appropriate statistical procedures, and conclusions were drawn on the basis of comparative analysis.

Sample

The sample consisted of 18 basketball players who regularly compete and train basketball for at least 6 years. Among them there were 10 juniors (17-18 years old), 4 cadets (15-16 years old) and 4 seniors (aged 30 (+/-4) years). All participants were included in regular training process and had a minimum of 8 training sessions per week. The minimum competitive experience was 4 years for each participant, while the seniors had at least 10 seasons of senior experience.

The participants were divided into two subgroups (“advanced” and “average”) based on their shooting success for two- and three-point shots, recorded in official statistics during the previous competitive season. The shooting per-

centage of advanced players was at least 40% and 30% for two- and three-point shots respectively, while percentages of the average subgroup were lower than mentioned values.

Protocol and measuring instruments

The test applied in this research involved performing dynamic shots from five different positions for both two-point (distance greater than 4.5 m and less than 6.75 m) and three-point shots (outside 6.75 m line). The shooting positions used in this test were determined based on the most frequently used shots in game – corners (parallel to the player shooting; on both sides of the backboard), 45-degree angles (on both sides of the backboard), and the central position in relation to the rim. The realization of the test was assisted by two passers (they pass the ball to the tested player who shoots), while in the third situation a defensive player was included. The players warmed up for 10 minutes before the test, after which the test protocol was explained to them.

The test was carried out in three situations:

- Situation 1 – dynamic shot from 2 set cones. The starting position is under the basket (cone No.1), from where, on the mark, the player moves in the full sprint to the position of the corner (marked cone No.2) and performs a shot, then returns with a light jog to the starting position and repeats the activity 5 times. The player performs this test from all 5 most characteristic shooting positions in a game.
- Situation 2 – the structure of the test is identical to situation 1, but before performing the shot, the player performs a motor task of anaerobic type (involving static pushing of an opponent for a duration of about 5 seconds), and then runs to the shooting position. The opponent (the player who participated in the static pushing) does not disturb the shooter during the shot; after 5 consecutive shots from one position, the players exchange roles.
- Situation 3 – includes a defensive player, who after pushing for duration of 5 seconds, has the task to move approximately one meter away from the pushing spot and by running toward the tested player who is shooting, tries to prevent (or to interfere with as much as possible) the shooter; after 5 consecutive shots from one position, the player switch roles.

In all three mentioned situations tests were carried out with both three-point shots (beyond the 6.75 m line) and two-point shots (distance greater than 4.5 m, but inside the 6.75 m).

Each successful attempt was awarded one point, while missed shots were recorded as zero (0), for each participant, the total number of points in two- and three-point shooting was recorded, as well as the individual scores for each shooting position.

Statistical analysis

The arithmetic mean (Mean) and standard deviation (SD) were calculated for each variable. The statistical signif-

icance of differences between the arithmetic means obtained in different groups of subjects and derived in different shooting situations was tested by combined analysis of variance – Mixed between-within subjects ANOVA (Tabachnick & Fidell, 2019). Two factors (two independent variables) were combined: the situation from which the shot is performed (between group variability) and the specificity of the groups (within group variability). A mixed 3x2 design (a matrix with three time points and two groups) was used for data comparison. The influence of independent variables (situations and groups), both combined (factor interaction) and separate, was estimated using Partial Eta Squared, η^2 , based on the criteria proposed by Cohen (1988). Combined variance analysis was conducted for the shooting percentage and for each position.

Before applying the variance analysis, the equality assumption of independent variables in different subgroups was checked using Levene's test (Levene test of Equality of Error Variances), as an important prerequisite for a valid interpretation of the variance analysis (Pallant, 2020). For a more detailed detection of the variability source between individual groups, a Post Hoc analysis was conducted using the Tukey HSD criterion.

The complete statistical analysis was performed using IBM SPSS 30.0, and all conclusions were conducted at a significant level of 0.05 ($p < 0.05$).

This study was approved in advance by the Ethics Committee of the Faculty of Sport and Psychology, Novi Sad. Each participant gave written consent to participate in the study.

Results

Descriptive data (Table 1) show that in situation 1, the differences in two-point shooting success are almost non-existent, as both subsamples performed similarly (Mean1=53.50, Mean2=53.20). In situation 2, a clear difference between the groups was recorded (when it comes to the success of the two-point shot – Mean1=56.00, Mean2=44.40). In situation 3, the difference between the groups was more pronounced than in the previous situation (Mean1=51.00, Mean2=36.80).

Before conducting the main analysis, assumptions about normality and homogeneity of variance were checked. Levine's test showed that there were no significant differences in the variances between groups ($Sig > 0.05$) in all two-point shooting ($Sig1=0.153$, $Sig2=0.940$, $Sig3=0.707$), which shows that groups are homogeneous and that conditions for the application of Mix ANOVA analysis were met (Table 2).

The results of the main analysis (Mix ANOVA) showed that the effect of situation was not statistically significant, suggesting that average two-point shooting percentage did not vary between the three situations. The interaction effect of the factor was not statistically significant ($Sig=0.26$), indicating that advanced and average did not show a different pattern of change in performance between situations (Table 3).

Table 1. Average values of two point shooting success in different groups and situations

	N	Group	Mean	Std. Deviation
Sit1.2p.percentage*	8	1 advanced	53.50	11.89
	10	2 average	53.20	19.50
	18	Total	53.33	16.11
Sit2.2p.percentage**	8	1 advanced	56.00	7.40
	10	2 average	44.40	8.90
	18	Total	49.55	9.61
Sit3.2p.percentage***	8	1 advanced	51.00	9.25
	10	2 average	36.80	13.43
	18	Total	43.11	13.55

Note. *two-point shooting percentages without the effect of inhibiting factors; **two-point shooting percentages affected by fatigue; ***two-point shooting percentages under the influence of fatigue and psychological stress.

Table 2. Results of Levine's test of homogeneity of groups in the two point shot

Situation	Levene Statistic	df1	df2	Sig.
Sit1.2p.percentage*	2.251	1	16	0.153
Sit2.2p.percentage**	0.006	1	16	0.940
Sit3.2p.percentage***	1.146	1	16	0.707

Note. *two-point shooting percentages without the effect of inhibiting factors; **two-point shooting percentages affected by fatigue; ***two-point shooting percentages under the influence of fatigue and psychological stress.

Table 3. Results of mixed analysis of variance (3x2) of two-point shooting success

Source of variation	F	df	Sig.	η^2 (partial)
Situation (within subjects)	2.37	1.37	0.013	0.13
Situation (between subjects)	7.82	1.16	0.01	0.33
Situation*group	1.40	1.37	0.26	0.08

The results of the Levine's test (Sig1=0.568, Sig2=0.923, Sig3=0.027), which refers to the data obtained during the three-point shot (Table 4), show that the assumption of homogeneity of variances of different groups is mostly fulfilled, and it is possible to analyze the results obtained with Mix ANOVA.

The results showed a statistically significant situation effect (shooting success varied, i.e. decreased as the situation became more complicated). The interaction effect of the factors

was not statistically significant (Sig=0.151). The group effect was significant (Sig=0.026), meaning that advanced subjects achieved a higher overall percentage of three-point shooting success compared to average subjects (Table 5).

The average values of two- and three-point shooting of the two groups of subjects in three different situations are graphically presented in the figures (Figure 1 and Figure 2).

Table 4. Results of Levin's test of homogeneity of groups using three-point shooting

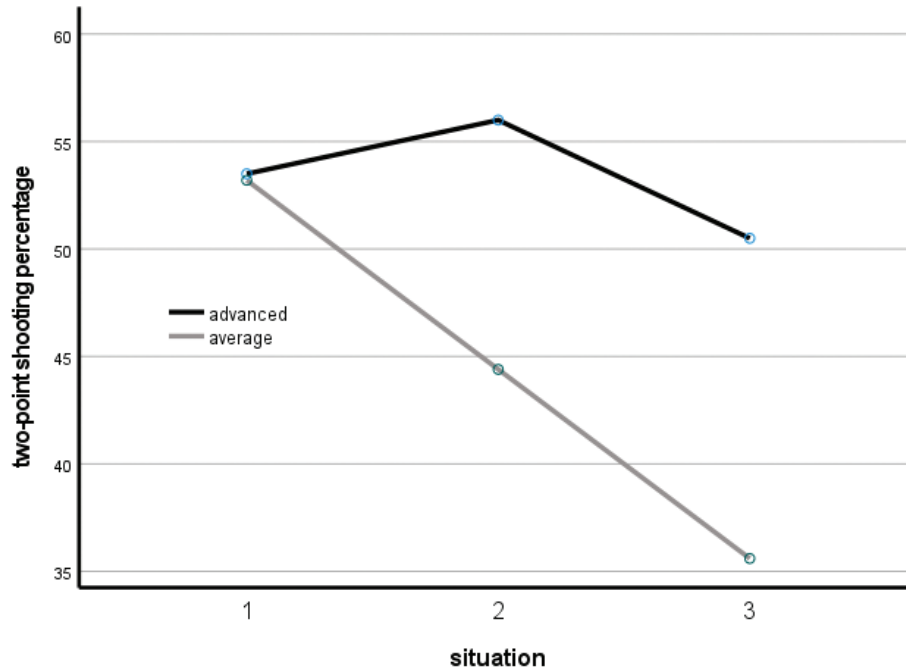
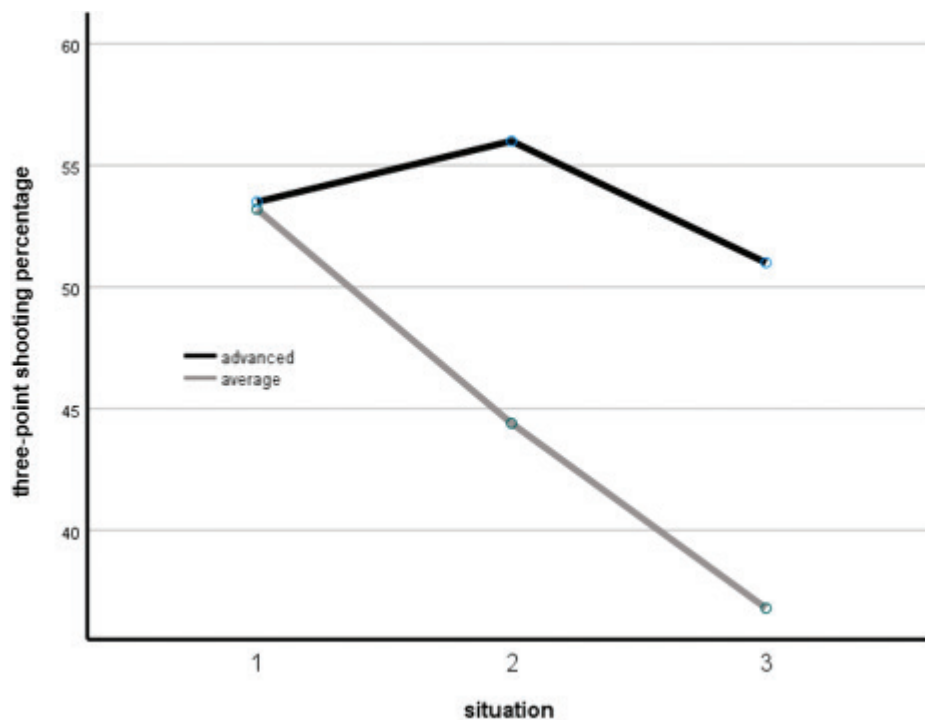
Situation	Leven statistic	df1	df2	Sig.
Sit1.3p.percentage*	0.340	1	16	0.568
Sit2.3p.percentage**	0.010	1	16	0.923
Sit3.3p.percentage***	5.943	1	16	0.027

*three-point shooting percentages without the effect of inhibiting factors; **three-point shooting percentages affected by fatigue; ***three-point shooting percentages under the influence of fatigue and psychological stress.

Table 5. Results of mixed analysis of variance (3x2) of three-point shooting success

Source of variation	F	Sig.	η^2 (partial)
Situation	8.23	0.001	0.34
Linear trend	10.74	0.005	0.40
Situation*group	2.11	0.151	0.12
Group	6.01	0.026	0.27

three-point shooting percentages without the effect of inhibiting factors; **three-point shooting percentages affected by fatigue;*three-point shooting percentages under the influence of fatigue and psychological stress.*

**Figure 1.** Average values of two-point shooting success in three situations**Figure 2.** Average values of three-point shooting success in three situations

Discussion

In this study, differences in success levels of two- and three-point shots were analyzed, with and without the presence of inhibiting factors, as well as their influence on different groups of basketball players within a team (advanced and average). Inhibiting factors in this study were fatigue and psychological stress, while shot percentages in the previous season were the determinant for dividing players into two groups. Traditional shooting trainings are realized in conditions without specific limitations (characteristic of competition conditions), despite a certain number of modern research studies, which show the negative impact of numerous factors (fatigue, psychological stress) on success of two- and three-point shots competition conditions (Bourdard et al., 2024; Li et al., 2024; Pojskić et al., 2018). In this study, the effects of different situations (without and with the presence of inhibiting factors such as fatigue and psychological stress), as well as the effect of groups (average and advanced players, according to shooting success percentage from the previous season), and the synergy of these factors on the success in two- and three-point shots were monitored, on sample of 18 basketball players competing in the senior rank of competition.

The results showed partial agreement with previous studies, and necessity for separate interpretation of the influence of the mentioned factors (group of situations and synergy of those two factors) on success in both two and three-point shots.

Analysis of the results, despite the decreasing trend of the percentage two-point shots under the influence of fatigue, shows that the effect of the situation (situation 2) does not significantly affect the performance. This research shows agreement with results of some previous studies (Bourdis et al., 2024; Pojskić, 2018) in which the influence of fatigue on the reduction of success in two-point shooting was confirmed, as well as that a higher level of anaerobic capacity increases the percentage of success in this shooting category. At the same time, such results are an indicator that the subjects who participated in this research have developed tolerance to loads in the anaerobic work regime, and that due to satisfactory physical preparedness fatigue does not affect the two-point shooting percentage. This study exhibited similar results in situation 3, when it comes to success in two-point shooting, where the inhibiting factor is psychological stress (with the previously included fatigue factor), which is in agreement with the results of some previous research (Morgulev, 2025). As reports from several studies confirm that numerous psychological factors influence shooting percentages in basketball (Bali, 2015; Lu & Li, 2022) and the results of this study confirm that one of them (psychological stress) does not statistically significantly affect success in two-point shooting, it is concluded that the selected sample of basketball players shows resistance to the influence of this inhibiting factor in this shooting category. As the group effect showed statistical significance (two-point shooting percentages) because the percentage of success for two points of the advanced group is significantly higher than that of the average group, the study reveals that player's quality influences performance in this category more than the inhibiting factors included in the conducted study.

Except of two-point shooting success, the aim of the re-

search was to record how different three-point shooting situations impact the success of basketball players of different skill levels (advanced-average). The findings of numerous studies (Gou & Zhang, 2022; Simović et al., 2022; Zajac et al., 2023), which show that three-point shooting success influences competition outcomes to a greater extent than two-point shooting, multiply the importance of analyzing the influence of inhibiting factors on performance in this category. The obtained results show that situational conditions affect the three-point shooting percentage and that there is a difference between the established groups which is statistically significant, as a consequence of the fatigue effect on technical demands (increase in the wrist and shoulder flexion, angle of ball entry, as well as the reduction of strength and velocity).

The results of this research confirm a significant effect of the situation, meaning that success in this category changes depending on the execution conditions. Obtained data are consistent with previous research (Kambič et al., 2022; Li et al., 2024; Rojas et al., 2000), which showed that more demanding situations decrease the technical stability of the execution (change of launch angle, higher launch speed, reduced angle of passage of the prop through the target) and the possibility of unwanted increases.

A significant linear trend indicates that performance in a three-point shot gradually changes through three situations, and those changes are not accidental, but the result of inhibition factors impact. The most prominent trend is seen in situation 3, when, besides the synergy of aforementioned factors, perceptual-cognitive factors may have role, such as visual attention and decision making speed (which were not the subject of this analysis).

The results also show a significant effect of the group, i.e., that the advanced basketball players of the team chosen for the research were more successful in all three-point shooting situations. These outcomes confirm expectations that more experienced basketball players with a higher level of basketball competence adapt more quickly to more complex execution conditions (prompt adaptation to psychological stress).

Due to the interaction of factors not showing statistical significance, it can be stated that the pattern of change in three-point shooting success across different situations did not fluctuate depending on the groups (advanced and average) reacted analogously to the increase in demands through three situations (both groups show a drop in success, but the advanced maintain a higher level of absolute effectiveness). This finding suggests that a more complex situation has a universal effect on outcomes, regardless of skill level.

Study limitation

One of the main limitations of the study stems from its realization on a very small sample. Increasing the sample in some future studies, as well as introducing top players of the opposite sex, would certainly contribute to the reliability of concluding. Another limitation stems from the small number and nature of instruments for assessing success in two and three-point shooting. Yet another limitation is expressed, and is a consequence of the absence of a more precise biomechanical analysis (the research showed a statistically significant

influence of the group on the success of two and three-point shooting, which suggests that quality of technique is of extreme importance).

In order to overcome the stated limitations, it is advisable to conduct research with an expanded sample (preferably of opposite sex), increase the number of measurement instruments, along with biomechanical analysis of the shooting technique, which would undoubtedly contribute to a more reliable generalization of the results.

Practical applications

Despite the limitations of the study, the results undoubtedly confirm that success in two-point and three-point shooting depends on both individual abilities and situational factors, whereby the effects of skill is reflected in a higher level of average success, not in the way subjects adapt to changing conditions. The results of this research are practically applicable to the training process (especially shooting trainings), because they indicate the importance of introducing situational elements during shooting training in order to influence the level of ability in real competition conditions.

The optimization of the training process is suggested through the integration of situational shooting training with various inhibiting factors (such as fatigue and psychological stress). As the results of the study show that fatigue and psychological stress can be a trainable component, their monitoring contribute to the long-term effectiveness of the training process.

The suggestions relate primarily to shooting training, in which the three-point shot is emphasized, because the inhibitory factors involved have shown a statistically significant impact on performance. Such suggestions do not bypass shooting training, in which the emphasis is placed on the two-point shot, because despite the fact that inhibitory factors have not shown a statistically significant impact on performance in this category, a decreasing trend in the percentage of shots under their influence has been registered.

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Conflicts of interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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Effects of Hydrogel-Based Sodium Bicarbonate Supplementation on Cycling Performance and Acid–Base Balance in Trained Cyclists: a Pilot Randomized Crossover Study

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Abstract

Sodium bicarbonate (SB) is a widely studied ergogenic aid for enhancing performance during high-intensity exercise. However, its practical use is often limited by gastrointestinal symptoms (GIS). This pilot, randomized, single-blind, placebo-controlled crossover study investigated the effects of SB in hydrogel form (SB-H) compared to a hydrogel placebo (PLA) in a small cohort of trained cyclists. Eight trained male cyclists completed both SB-H and PLA conditions in a crossover design, separated by a 7-day washout period. Performance variables, blood electrolytes, acid–base balance, and GIS were assessed during a time-to-exhaustion cycling test. SB-H supplementation improved performance, with a 7% increase in power output at the 2 mmol/L and a 15% increase at the 4 mmol/L lactate thresholds compared to PLA. Time to exhaustion was significantly longer with SB-H, and heart rate at the 4 mmol/L threshold was lower, suggesting improved cardiovascular efficiency. SB-H also mitigated exercise-induced metabolic acidosis, with higher post-exercise sodium and lower chloride levels, likely due to sweat-related electrolyte shifts. Importantly, GIS scores remained low in both groups, with SB-H demonstrating superior tolerability. This pilot study suggests that SB-H supplementation enhances high-intensity cycling performance, improves acid–base regulation, and reduces gastrointestinal discomfort. These findings provide preliminary effect size estimates and feasibility data that support further investigation in larger, fully powered trials.

Keywords: sodium bicarbonate, hydrogel supplementation, ergogenic aid, cycling performance, gastrointestinal tolerance

Introduction

Sodium bicarbonate (SB) is a widely recognized extracellular buffer used to enhance performance during high-intensity muscular endurance activities such as cycling (Grgic et al., 2021). During anaerobic glycolysis, the accumulation of hydrogen ions (H⁺) reduces intramuscular pH, impairs the activity of glycolytic enzymes, inhibits calcium binding in the sarcoplasmic reticulum, and accelerates the onset of fatigue (Gaskell et al., 2023; Gough et al., 2024; Hilton et al., 2020).

Supplementation with SB increases the concentration of bicarbonate ions (HCO₃⁻) in the blood, increasing the body's ability to buffer excess H⁺, maintain acid-base homeostasis, and sustain exercise performance (Shannon et al., 2024).

To overcome these limitations, alternative delivery strategies have been proposed, including dose titration, enteric-coated capsules, and more recently, hydrogel-based formulations (Gaskell et al., 2023; Hilton et al., 2020; Shannon et al., 2024). A recent review (Grgic et al., 2021) summarized data

from nearly 200 cyclists across three decades and highlighted the limited number of studies with trained athletes, consistent exercise protocols, or novel formulations. Moreover, most investigations used uncoated SB, contributing to inconsistent results regarding performance outcomes such as time to exhaustion and power output (Ferreira et al., 2019; Gough et al., 2022; Horswill et al., 1988; McNaughton et al., 1992; Schauf et al., 1996; Yong et al., 2018).

Few studies have explored the potential of sodium bicarbonate hydrogel (SB-H), which may offer improved tolerability of gastrointestinal (GI) side effects and buffering capacity. Although initial results are promising, the available evidence is scarce and somewhat conflicting. The study by Gough et al. (2022) found no significant effects of SB-H supplementation on blood electrolyte levels, whereas Shannon et al. reported marked alterations in acid–base parameters under comparable conditions (Ferreira et al., 2019; Shannon et al., 2024). These discrepancies may arise from methodological variability and reinforce the need for controlled clinical trials in well-trained populations.

Thus, the objective of this pilot crossover study was to evaluate whether high-dose sodium bicarbonate, administered in hydrogel form, improves blood acid–base balance, enhances performance, and reduces GIS in trained cyclists during a time-to-exhaustion protocol. Given the exploratory nature of this investigation, the study was designed to generate feasibility data and preliminary effect size estimates to inform the design of future fully powered trials.

Materials and methods

Participants and design

Participants were randomly assigned to supplementation conditions using a computer-generated random sequence. The study followed a randomized, longitudinal, single-blind, crossover design, with each participant completing both experimental conditions (SB-H and placebo) in a randomized

order, separated by a 7-day washout period to avoid carryover effects. The study was single-blind, with participants unaware of the supplement content (SB-H or placebo), while researchers were aware for protocol administration purposes.

Eight trained male cyclists participated in this study (age: 41.5 ± 5.7 years; body mass: 71.8 ± 6.5 kg; height: 1.72 ± 0.05 m; cycling activity: 11 ± 9.3 hours per week). Inclusion criteria required participants to have no history of chronic metabolic or musculoskeletal diseases and to engage in at least 3 hours of cycling per week. The study was approved by the Ethics Committee of FAMERP Medical School (São José do Rio Preto, Brazil; permit number: 661258), and informed consent was obtained from all participants.

Procedures

Participants initially underwent biochemical analyses to assess serum markers related to metabolic processes and electrolyte balance. This included measurements of serum creatine phosphokinase (CPK), pH, lactate, sodium (Na^+), potassium (K^+), sodium bicarbonate (NaHCO_3), serum creatinine (sCr), and chloride (Cl^-). The anion gap was calculated as previously described (Kraut & Madias, 2007).

Simultaneously, physiological responses during exercise were monitored. Heart rate (HR) was continuously recorded throughout the exercise test to assess fluctuations indicative of cardiovascular strain and adaptation. Power output, a key measure of exercise intensity and performance, was recorded using each participant's bike mounted on a cycling ergometer. The experimental protocol consisted of three non-consecutive sessions: (a) pre-exercise assessment (Pre-Exc); (b) ingestion of $0.3 \text{ g}\cdot\text{kg}^{-1}$ SB in hydrogel form followed by incremental ramp exercise (SB-H); and (c) ingestion of placebo hydrogel (PLA) without SB followed by the same protocol (Figure 1). The within-subject crossover design was chosen to minimize inter-individual variability and improve statistical power, which is particularly relevant in small sample pilot studies.

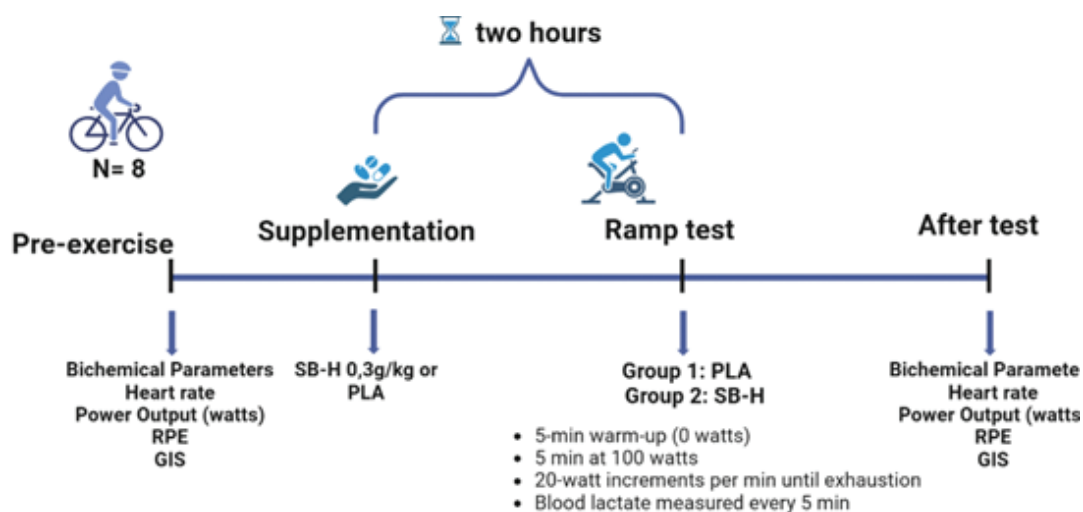


Figure 1. Schematic overview of the experimental test

Note. This single-blind, randomized study involved eight cyclists, assessing biochemical parameters, heart rate, power output, perceived exertion (RPE), and gastrointestinal symptoms (GIS). The study groups were as follows: PLA (placebo), SB-H (sodium bicarbonate supplementation in hydrogel form), and pre-exercise (no supplement).

Supplementation protocol

SB in hydrogel form (Maurten Bicarb System[®]) was administered at 0.3 g/kg body mass, two hours before the exercise protocol (Maurten Bicarb System, 2025). Placebo supplement was formulated to mimic the Maurten brand's sodium bicarbonate hydrogel closely, containing 3 g of xanthan gum, 20 g of maltodextrin, 20 g of sucralose, and 20 g of sugar spheres, ensuring both supplements had an identical appearance. They were distributed to participants in individual packages, each labeled with the participant's name.

Training protocol

Participants were instructed not to use additional buffering aids or intracellular buffers during training, and to abstain from nutritional, pharmacological, and hormonal ergogenic aids for at least 30 days prior to the study. Participants avoided strenuous exercise for 48 h, did no exercise, and did not drink alcohol for 24 h. Breakfast was consumed 3 h before the start of the warm-up, with caffeine intake restricted. After that, only water intake was allowed.

SB-H or PLA was taken 2 h before the start of the exercise. This timing was selected based on evidence indicating that peak blood bicarbonate concentrations occur approximately 2 h after ingestion, thereby optimizing extracellular buffering during the exercise protocol (Maurten Bicarb System, 2025).

The Wahoo KICKR Power Trainer was used, with the Wahoo Blue SC speed and cadence sensor, validated by Zadow et al. (2016) with power and cadence data accurately captured via Zwift simulation software. All sessions were conducted in the morning under controlled ambient conditions and temperatures.

The protocol began with a five-minute warm-up phase of free exercise, followed by a second five-minute phase of 100 W training. The third phase involved 20-watt per minute increases from 100 W, with blood lactate levels measured every five minutes using a Lactate Plus meter (Nova Biomedical, MA). This ramp protocol is consistent with validated methodologies for determining time to exhaustion and physiological thresholds. Exercise was considered complete when the participant reached exhaustion, defined as the point at which they could no longer produce sufficient power to meet the increasing power demands of the equipment. Post-testing, the Borg CR10 Scale of Perceived Exertion (RPE - 0-10) was used to assess perceived exertion levels during exercise (Williams, 2017).

GIS - Questionnaire

The GIS assessment tool was employed to quantify self-reported gastrointestinal symptoms, as described previously (Gaskell et al., 2023). Participants were instructed on how to use the GIS rating scale, where a score of 1–4 indicates mild symptoms, 5–9 represents severe symptoms, and a score of 10 indicates extremely severe symptoms necessitating the cessation of exercise. If no symptoms were reported, a score of 0 was recorded. The questionnaire assessed nine symptoms, including bloating, nausea, abdominal pain, belching, flatu-

lence, and vomiting. The tool was administered 30 minutes post-exercise by a trained researcher to capture acute gastrointestinal responses while minimizing reporting bias (Souza et al., 2016).

Statistical analysis

Normality of quantitative variables was assessed using the Kolmogorov–Smirnov test. Given the crossover design, all comparisons between experimental conditions (SB-H vs. PLA) were performed using paired statistical tests. For normally distributed data, the paired Student's t-test was applied; for non-normally distributed data, the Wilcoxon signed-rank test was used. When more than two conditions were compared (e.g., including Pre-Exc), the repeated-measures Kruskal–Wallis test followed by Dunn's post hoc test was employed.

For categorical variables, comparisons of frequencies were conducted using the McNemar test for paired proportions or Chi-square test when appropriate. Statistical significance was set at $p < 0.05$. All analyses were performed using GraphPad Prism, version 9.1 (GraphPad Software Inc., USA). As this was a pilot crossover study, no a priori sample size calculation was performed; instead, effect sizes were estimated to inform the design of future fully powered trials. The randomized crossover design, in which each participant served as their own control, was chosen to reduce interindividual variability and partially compensate for the small sample size, increasing sensitivity for within-subject comparisons.

Results

Given the pilot nature of the study, the results below emphasize outcomes with the greatest physiological and practical relevance, particularly power output at the 4 mmol/L lactate threshold, HR responses, and time to exhaustion.

Blood acid-base balance, lactate levels, and electrolyte response

The efficacy of the endurance cycling protocol was evidenced by significant reductions in plasma pH, SB, and chloride levels, along with increases in anion gap, lactate, and blood CPK levels in the PLA and SB-H groups when compared to pre-exercise values (Table 1 and Figure 2). During the pre-exercise phase, blood pH remained within the normal range. However, cycling performance induced metabolic acidosis, resulting in decreased pH in the SB-H and PLA groups ($p = 0.007$ and $p = 0.01$, respectively). This acidosis was accompanied by a four- and five-fold increase in blood lactate levels in the PLA and SB-H groups, respectively, which correlated with an increase in the anion gap of both exercise groups. Despite the acid–base disturbance, performance capacity was preserved, suggesting that SB-H may have contributed to the maintenance of muscular function under acidotic conditions (Figure 2). Higher plasma sodium concentrations (PLA: $p = 0.04$; SB-H: $p < 0.0001$) and lower chloride levels (PLA: $p = 0.04$; SB-H: $p = 0.0002$) were observed in both cycling groups compared to pre-exercise values.

Table 1. Blood tests pre and post ingestion of bicarbonate hydrogel (SB-H) or placebo (PLA)

Variables	Pre-Exc	PLA	SB-H	*p-value (Pre-Exc vs Pla)	**p-value (Pre-Exc vs SB-H)	***p-value (SB-H vs Pla)
NaHCO ₃ (mmol/L)	28±1.5	19±5.3	19±3.6	0.0005	<0.0001	0.84
Serum creatinine (mg/dL)	1±0.18	1±0.42	1±0.19	1	1	1
CPK (U/L)	192±173	260±221	427±420	0.008	0.03	0.07
Plasma Na ⁺ (mM)	141±1.3	143±2	146±2.4	0.04	<0.0001	0.009
Plasma K ⁺ (mEq/L)	4.7±1.2	4±0.31	4.3±0.4	0.1	0.37	0.10
Plasma Cl ⁻ (mEq/L)	102±1.3	100±2.8	99 ±1.55	0.04	0.0002	0.25

Note. NaHCO₃: Sodium bicarbonate; CPK: Creatine Phosphokinase; Na⁺: sodium; K⁺: potassium; Cl⁻: Chloride. p*=significance between: Pre-Exc and placebo groups; p**=significance between Pre-Exc and SB-H groups; p***=significance between SB-H and PLA groups. Data are presented as mean±SD.

Serum creatinine and plasma K⁺ levels remained unchanged pre- and post-exercise in both groups. However, CPK levels increased significantly, with a 35% rise in the PLA group and a 122% rise in the SB-H group compared to pre-exercise levels (p=0.008 and p=0.03, respectively). These increases sug-

gest a physiological response to prolonged or intense physical activity. The marked increase in CPK, particularly in the SB-H condition, may reflect a greater muscular effort and metabolic stress response, possibly associated with enhanced exercise performance.

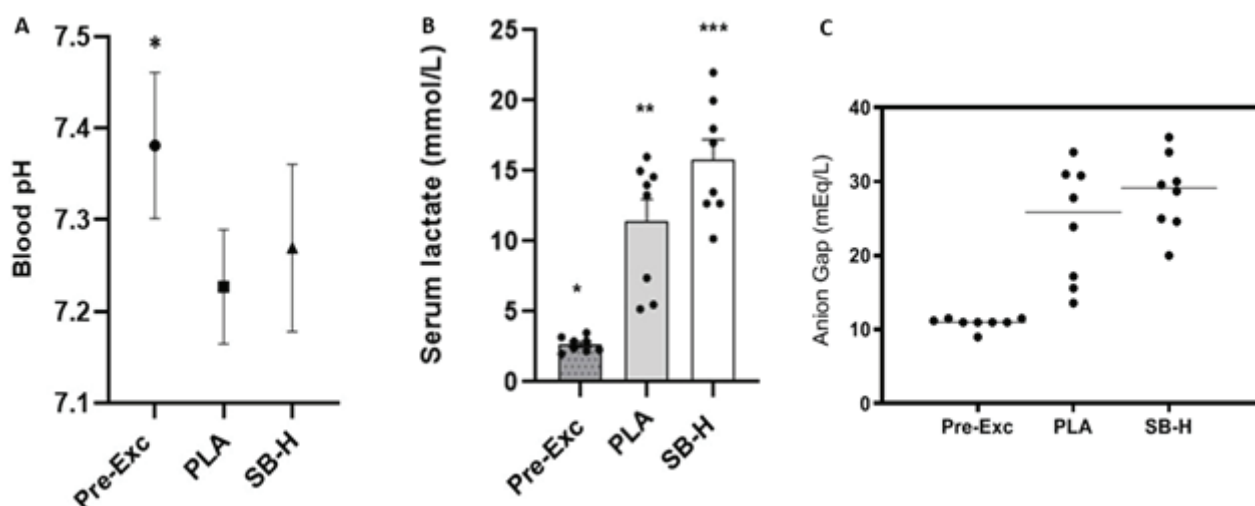


Figure 2. Effects of sodium bicarbonate in hydrogel form (SB-H) and placebo (PLA) physiological responses

Note. Blood pH (A), serum lactate (B), and anion gap (C) before exercise (Pre-Exc) and after placebo (PLA) or sodium bicarbonate hydrogel (SB-H) supplementation. (A) Pre-Exc had higher pH than PLA and SB-H (*P=0.007, 0.01). (B) Serum lactate was higher in PLA than Pre-Exc and SB-H groups (*P=0.001, **P=0.04, ***P=0.002). (C) Anion gap was higher in Pre-Exc than PLA and SB-H groups (*P=0.007 and 0.01 respectively). Data are presented as mean±SEM.

Exercise performance

The effects of SB-H supplementation on power output, HR, and time to exhaustion at lactate concentrations of 2 and 4 mM are presented in Figure 3. At 2 mM lactate, the SB-H group exhibited a 7% increase in power output (equivalent to 12 W) compared to the PLA group, although this difference

was not statistically significant. Nevertheless, this magnitude of improvement may hold biological relevance, particularly in submaximal or pacing-based efforts where small gains in power can yield performance advantages. At 4 mmol/L lactate, the SB-H group demonstrated a significantly higher power output than the PLA group, highlighting a clear energetic advantage associated with supplementation.

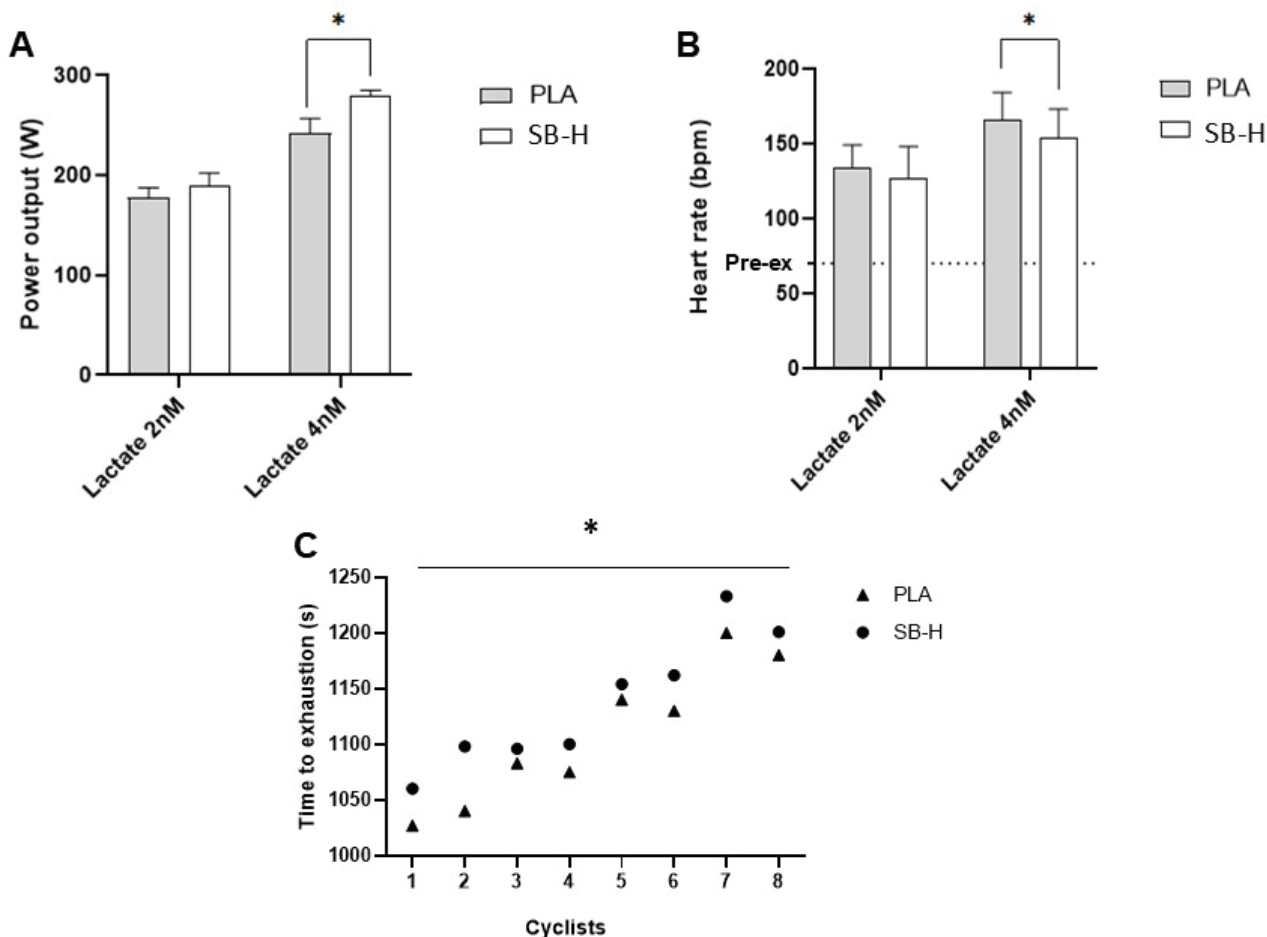


Figure 3. Impact of bicarbonate supplementation on power output, heart rate (HR) and time to exhaustion

Note. A) Power output at lactate 2mM and 4mM, * $p=0.02$; B) HR at the 2mM and 4mM lactate level, * $p=0.009$ (values of Pre-Exc are set at 70 bpm); C) Time to exhaustion comparison between PLA and SB-H, * $p=0.001$. Data are presented as mean \pm SD.

Regarding HR, no significant differences were observed between the groups at 2 mmol/L lactate. At 4 mmol/L lactate, however, the SB-H group exhibited a significantly lower HR, suggesting reduced cardiovascular strain and potentially enhanced physiological efficiency during high-intensity efforts.

The time to exhaustion was longer in the SB-H group compared to the PLA group ($p=0.001$), further indicating that SB-H supplementation may extend endurance capacity under increasing workload conditions.

Gastrointestinal side effects

The responses to the GIS questionnaire revealed no statistically significant differences in total symptom scores between the SB-H and PLA groups, as shown in Figure 4. Both groups reported generally low levels of GIS across the evaluated metrics. For example, stomach bloating was reported with mild frequency in both groups, while symptoms such as flatulence, nausea, and belching exhibited slight variations but remained minimal overall. No severe gastrointestinal symptoms, such as diarrhea and vomiting, were reported by any participant in either group.

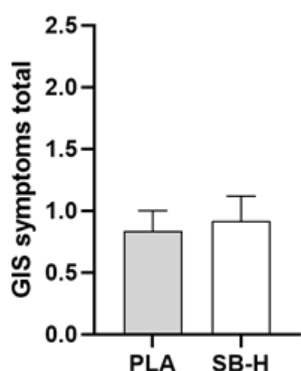


Figure 4. Comparison of gastrointestinal symptoms (GIS) total scores between PLA (placebo) and SB-H (sodium bicarbonate in hydrogel form) groups

Note. The GIS total score represents the incidence and severity of symptoms reported by participants, with no significant differences observed between the groups. Data are presented as mean \pm SD.

Discussion

SB supplementation has been widely recognized for its ergogenic properties, primarily due to its ability to buffer metabolic acidosis and sustain anaerobic energy production during high-intensity efforts (Lancha et al., 2015). The extracellular buffering provided by SB delays the drop in intramuscular pH, preserving enzymatic activity and calcium handling, thereby supporting muscle contractility and delaying fatigue (Lancha et al., 2015).

Although SB supplementation did not restore blood pH to pre-exercise levels, it allowed cyclists to improve their ergogenic performance despite elevated blood lactate concentrations and comparable anion gap values relative to the PLA group. This reflects the capacity of SB-H to enhance systemic buffering without fully normalizing pH, suggesting effective compensation rather than total correction. This alkalinizing effect facilitates the neutralization of hydrogen ions (H^+) produced during intense exercise, thereby delaying muscle fatigue (Grgic & Mikulic, 2022; Lancha et al., 2015).

The higher lactate levels observed in the SB-H group, when compared to PLA, suggest increased glycolytic flux and greater reliance on anaerobic metabolism (Correia-Oliveira et al., 2017; Zagatto et al., 2012). Importantly, this was not accompanied by premature exhaustion, indicating that SB-H supported sustained metabolic activity even under high lactate conditions. These dual effects reinforce the role of SB not only in buffering acidosis but also in sustaining energy output during high-intensity exercise, in line with previous research (Grgic & Mikulic, 2022; Lancha et al., 2015).

Performance improvements were especially evident at the 4 mmol/L lactate threshold, where the SB-H group demonstrated significantly higher power outputs. This supports the hypothesis that SB-H supplementation enhances extracellular buffering, improves metabolic efficiency, and delays neuromuscular fatigue under anaerobic stress (Correia-Oliveira et al., 2017; Grgic & Mikulic, 2022).

Furthermore, the longer time to exhaustion and the reduced HR at the 4 mmol/L threshold reinforce SB-H's ergogenic potential. The lower HR may reflect improved cardiovascular efficiency or enhanced peripheral muscle oxygen utilization, both of which are critical to prolonged performance in endurance and high-intensity interval modalities (Brisola et al., 2015; Cameron et al., 2010; Carr et al., 2011; Freis et al., 2017; Gurton et al., 2021). From an applied perspective, a lower HR at a fixed lactate threshold may allow cyclists to sustain higher workloads with reduced cardiovascular strain, thereby facilitating more efficient pacing during threshold and high-intensity efforts.

Our results align with those of Shannon et al. (2024), who also demonstrated improved cycling performance and superior GI tolerability using a hydrogel-based bicarbonate formulation. While their study emphasized prolonged aerobic performance, ours focused on high-intensity anaerobic conditions, extending the translational relevance of SB-H to sprint-based or threshold training contexts. Notably, the 7% increase in power output at 2 mmol/L lactate, although not statistically significant, holds biological relevance, particularly in settings where submaximal effort optimization is critical

for pacing strategies and endurance outcomes.

The low incidence of GIS reported with SB-H underscores the practicality of this delivery method. Mitigating the common adverse effects of bicarbonate such as bloating, cramping, and nausea has been a longstanding challenge, and the hydrogel formulation appears to overcome this barrier effectively (Carr et al., 2011; Hilton et al., 2020; Shannon et al., 2024).

In our view, the absence of a traditional SB comparison group does not represent a methodological gap, as the effects of uncoated or conventional SB supplementation are already extensively described in the literature (Ferreira et al., 2019; Grgic et al., 2021; Yong et al., 2018). Rather, this study was specifically designed to evaluate the performance and physiological response to a hydrogel formulation, which remains underexplored despite promising results in previous trials. Our findings contribute to this underrepresented area and provide additional insights into the utility of SB-H in high-intensity settings.

The lack of significant alterations in sCr, potassium, and the absence of clinical muscle damage (despite elevated CPK) further support the safety profile of SB-H supplementation (Grgic et al., 2021; McKenna et al., 2008; McNaughton et al., 2008; Wang et al., 2020). This is particularly relevant given recent concerns regarding the renal and muscular impact of chronic supplementation protocols in athletes.

Previous studies have yielded mixed findings regarding the performance-enhancing effects of SB (Mildenhall et al., 2023) observed attenuation of acid-base disturbances without improvements in supramaximal cycling performance, while Correia-Oliveira et al. (2017) found that pre-exercise alkalosis preserved anaerobic energy output during a 4-km time trial. Our findings add to this body of evidence, indicating that the hydrogel formulation provides a viable compromise between efficacy and tolerability, with measurable benefits under controlled, incremental-intensity exercise protocols.

A major strength of this study lies in its randomized crossover design, which allows each participant to serve as their own control, thereby eliminating interindividual variability. This statistical advantage increases sensitivity to detect within-subject differences, even in small samples, and enhances the reliability of effect-size estimation especially relevant in pilot trials where feasibility and biological plausibility are primary goals.

Nonetheless, this study has several limitations inherent to its pilot design. The small sample size limits generalizability and statistical power for some comparisons, and the cohort was composed exclusively of male participants, which precludes sex-specific analysis. Although the randomized crossover design strengthens internal validity by reducing interindividual variability, the absence of a conventional sodium bicarbonate comparison group should also be acknowledged.

Despite these limitations, the findings suggest that SB-H enhances performance in high-intensity cycling by improving power output, extending time to exhaustion, stabilizing acid-base balance, and minimizing GIS. These results should be interpreted as preliminary and hypothesis-generating, and support SB-H as a promising and well-tolerated ergogenic aid,

with direct implications for training and competition strategies in endurance and high-performance athletes.

Conclusions

Hydrogel-based sodium bicarbonate supplementation improved key performance outcomes during high-intensity cycling, including higher power output at the 4 mmol/L lactate threshold and longer time to exhaustion, while preserving cardiovascular efficiency and minimizing gastrointestinal discomfort. Although metabolic acidosis was not fully corrected, SB-H effectively enhanced extracellular buffering capacity, supporting sustained glycolytic activity and delaying fatigue under progressively demanding workloads. The absence of adverse renal or electrolyte disturbances further reinforces the safety profile of this formulation. Overall, SB-H emerges as a practical and well-tolerated ergogenic strategy, with particular relevance for threshold-based efforts, time trials, and high-intensity or anaerobically demanding cycling contexts.

Acknowledgments

There are no acknowledgments.

Conflicts of interest

The authors declare no conflict of interest.

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Correlation Between Body Mass Index, Self-Esteem and Stress Among Female Handball Players

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Abstract

This study aimed to investigate the correlation between body mass index, self-esteem, and stress among female handball players. In addition, it explores the differences in the level of stress and Self-esteem according to body mass index (BMI) and years of training. A total of 122 elite handball players participated in this study, with age, height, body mass, and body mass index assessed and expressed as mean \pm standard deviation: 21.5 \pm 3.5 years, 1.69 \pm 0.09 m, 65.5 \pm 4.47 kg, and 22.94 \pm 3.52 kg/m², respectively. The applied the Self-esteem test (SEs) and perceived stress test (PS-s) to obtain the study data. The study's objectives were achieved by applying means, standard deviations, and one-way ANOVA analysis, with a confidence level of 95%. The study results revealed that a moderate level of the PS-s test (14.31) according to the scoring PS-s test, and there are statistically significant differences in PS-s according to the BMI variable and in favour of the normal category (12.95). Simultaneously, the level of perceived stress increased with the increase in the BMI category. However, the self-esteem level was high in general (32.50). Notably, all BMI categories achieved high levels of self-esteem with an advantage over the normal weight category (35.98). The current study showed a statistically significant association between BMI and stress level ($r=0.253$). Based on the results, further studies can focus on gender and play position variables.

Keywords: years of training, sport, categories, play position, self-concept, female athletes

Introduction

Sports and games are part of physical education and essential for the growth and development of individuals' physical, mental, and psychological aspects (Shiroli & Makawana, 2021). Handball is a dynamic team sport that imposes various high-level requirements on players (Sindik & Cuk, 2022). In addition, handball involves fast, force, and precise movements. Therefore, the psychological pressures on players are high, which confirms that the performance quality during sports competitions is affected by the player's psychological state (Jose & Sudheesh, 2020). In this regard, Wagner and Muller (2008) studied; the success in handball does not depend only on the player's physical fitness but also on their mental and psychological abilities, as is the case with any team

sport, as the final result depends mainly on the psychological and physical participation of the players, as well as the players' ability to cooperate.

Accordingly, all factors affecting the performance of athletes, especially in competitions, must be carefully considered by identifying the desired positive, strong, and weak personal qualities (Piepiora & Kazmierczak, 2020). In the same context, one of the psychological aspects affecting the performance of handball players is stress, which has strangely become a significant health problem according to the World Health Organization, which classified it as a health epidemic in the twenty-first century, because stress is a physiological mechanism for the body to adapt for the environment, which is necessary for recovery (Singh et al., 2019). Stress refers to the body's response to influential stressors, in other words, the response of

the nervous and immune systems to the external or internal load of athletes (Kaplanov & Gregor, 2019). Thus, psychological skills affect sports performance positively or negatively (Jose & Sudheesh, 2020).

Another psychological aspect is self-esteem, which refers to an individual's ability to think and deal with fundamental challenges in life, and it refers to what we think about ourselves (Satiners & Sandeep, 2018). Sharma et al. (2018) studied; also indicate that self-esteem is one of the specific sports personality dimensions, and female participation in sports contributes to developing leadership skills and self-esteem. Self-esteem is a positive feeling toward oneself and is often a critical factor in healthy growth and development (Chen et al., 2007). Self-esteem is also considered a protective factor to avoid emotions of anger and stress in sports (Munoz-Villeina et al., 2020). Studies have shown that individuals with low self-esteem recover from negative events much more slowly than those with high self-esteem (Sedikides et al., 2004). Esroy and Abdullah (2021) also indicate that self-esteem among handball players was below average.

On the other hand, Anthropometric parameters and fitness elements determine handball player performance (Michalsik & Aagaad, 2015). For example, backs, centers, and goalkeepers have higher anthropometric requirements than wingers, who are players with lower body mass and shorter (Feseler et al., 2017). When reviewing the theoretical literature on this study topic, the researchers found that overweight status was associated with poor self-esteem (Chen et al., 2007). Also, high body mass index (BMI) was associated with negative psychosocial responses that affect self-esteem (Stoerber et al., 2008). In addition, a negative association exists between high BMI and self-esteem (Anwar et al., 2020; Ortega Becerra et al., 2015). In the same context, Maciej et al. (2023) indicated that BMI was associated with a non-statistically significant

relationship between self-esteem and depression.

The current study's importance is highlighted by its discussion of the BMI associated with body image and the attempt to explore the effect of this variable on the psychological aspects (stress and self-esteem) among female handball players. The problem of this study crystallized from several aspects, the most important of which is that handball coaches focus on physical, skill, and tactical training, with a clear decline in psychological training. There has also been a decline in scientific studies focusing on female handball players. Researchers believe that the methodology of modern sports training includes multiple aspects to ensure that players adapt to the requirements of intense effort in competitions, training, and effective recovery after effort. Therefore, the novelty of this study lies in filling gaps in the scientific literature on psychological aspects and linking them to BMI among female handball players in the Arab environment. The study results can serve as a guide when selecting female handball players.

In addition, a primary aim of the study was to investigate the correlation between body mass index, self-esteem, and stress among female handball players. In addition, the secondary aim of the study was to explore the differences in the level of stress and Self-esteem according to body mass index (BMI) and years of training

Materials and methods

Participants

This analytical research used the descriptive approach during the 2024/2025 sports season. This study was conducted on (122) female handball players affiliated with clubs participating in the local league. Participants in the current study were also selected using the random sampling method. The study sample's demographic characteristics are shown in Table 1.

Table 1. The demographic characteristics of the study sample

Variables	Mean	Std. Deviation	Skewness
High/m	1.69	0.09	0.93
Mass/kg	65.50	4.70	0.53
Age/year	21.50	3.60	0.04
BMI(kg/m ²)	22.94	3.52	0.88
Years of training	7.50	2.50	0.92

Additionally, the researchers checked the data's skewness values (0.042-0.93). As a result of the statistical process, it was determined that the data were in the range of -1,.,, +1 (George & Mallery, 2019), which are considered suitable for normal distribution. The study sample participated only by completing the electronic questionnaire, and the researchers clarified the purpose of the current study and that the data obtained would be treated confidentially. The first paragraph included approval to participate in the current study. In addition, written consent was obtained from each female handball player, as well as from her guardian.

Self-esteem scale (SE-s)

The Self-Esteem Scale (SE-s) is used most to measure self-esteem. It has been used in several fields and has demonstrated comparable stability in many cultures (Park & Park, 2019). In addition, the (SE-s) is a 10-item scale that measures global self-worth by measuring both positive (items: 1, 3, 4, 7, 10) and negative (items: 2, 5, 6, 8, 10) feelings about the self. All items are answered using a 4-point Likert scale ranging from strongly agree to disagree strongly. Scoring: Items 2, 5, 6, 8, and 9 are reverse scored by giving 1 - Strongly Disagree, 2 - Disagree, 3 - Agree, and 4 - Strongly Agree. Sum scores for

all ten items. The scale ranges from 0-40. Scores between 20 and 30 are within the normal range; scores below 20 suggest low self-esteem (Ciarrochi et al., 2007).

Perceived Stress Scale (PS-s)

The Perceived Stress Scale (PS-s) is a 10-item scale; the questions in this scale ask about your feelings and thoughts during the last month. In each case, you will be asked to indicate how often you felt or thought a certain way. All items are answered using a 4-point Likert scale ranging from never to very often. Scoring is as follows: the scores of Items 1, 2, 3, 6, 9, and 10 like this: 0 - never, 1 - almost never, 2 - sometimes, 3 - fairly often, and 4 - very often. However, the scores of Items 4, 5, 7, and 8 are like this: 4 - never, 3 - almost never, 2 - sometimes, 1 - fairly often, and 0 - very often. Additionally, the Individual scores on the PSs can range from 0 to 40, with higher scores indicating higher perceived stress. Scores ranging from 0-13 would be considered low stress; scores ranging from 14-26 would be considered moderate stress, and scores ranging from 27-40 would be considered high perceived stress (Cohen & Janicki-Deverts, 2012).

To adapt the (SE-s and PS-s) scales, the researchers translated the original version from English into Arabic. Then, they sent the original and translated versions to three university professors in sociology and psychology to evaluate and review the translation. The researchers then revised the translated version based on the reviewer’s comments and then submitted it again to a translation expert to review the linguistic accuracy of the translated scale.

Applying the (SE-s and PS-s) scales test for the study sample

After adopting the (SE-s and PSs) scales, to facilitate the response process of the study sample, the researchers put the (SE-s and PSs) items in an electronic questionnaire using (Google Forms). They sent the link to the participants via the WhatsApp application and the official website of the Jordanian Handball Federation. It is worth noting that the first

paragraph of the electronic questionnaire requests consent to participate in this study. Accordingly, the researchers sent the study tool on 30/8/2024 and continued to receive responses for four weeks.

Body mass index (BMI)

The body mass index (BMI), an anthropometric indicator commonly used in studies with athlete populations, was calculated using the following formula: $BMI = BW/h^2$. Where: $BMI (kg/m^2) = Body Mass (BW) (kg) / Height (h) (m)$. Furthermore, it is categorized using the World Health Organization (WHO) cut-off points. BMI categories can be classified (normal: 18.5 - less than 25 kg/m^2 , overweight: 25 - less than 30 kg/m^2 and first-degree Obesity: 30 - less than 35 kg/m^2).

Reliability

In the current study, the Cronbach alpha coefficients of the measurement tool are (0.82) for the (SE-s) scale and (0.85) for the (PS-s) scale, which are values close to (1). It can be said that this result is quite reliable according to (Karagöz, 2017).

Data analysis

For illustrative purposes, we used means and standard deviations as descriptive statistics for the study variables. In addition, we used a one-way ANOVA test to detect differences in means of (SE-s and PSs) items according to the BMI and years of training variables. Pearson’s correlation coefficient was also used to detect potential relationships between study variables using SPSS version 24 with a confidence level of 95% ($p < 0.05$).

Results

The data was collected from female handball and descriptive statistics of SE-e, PSs items and BMI for female handball players are shown in Table 2. Furthermore, the differences in SE-e and PSs items according to female handball BMI are shown in Table 3.

Table 2. Shows the descriptive statistics of SE-e, PSs items and BMI for female handball players

Scale	*Group- kg/m^2	N	Mean	SD	Level
Perceived Stress	Less than 25	78	12.95	3.03	Low
	25- less than 30	34	16.52	3.55	Moderate
	30 and above	10	17.40	4.34	Moderate
	Total	122	14.31	3.97	Moderate
Self-esteem	Less than 25	78	35.98	2.47	High
	25- less than 30	34	32.56	2.12	High
	30 and above	10	30.40	2.43	High
	Total	122	32.50	2.62	High

*Note: Normal: 18.5 - less than 25 kg/m^2 , Overweight: 25 - less than 30 kg/m^2 and Obesity first-degree: 30 - less than 35 kg/m^2

Table 3. Shows the differences in SE-e and PSs items according to female handball BMI (n=122)

Scale		Sum of Squares	df	Mean Square	F	Sig.
Perceived Stress	Between Groups	407.49	2	203.749	4.42	0.014*
	Within Groups	5474.66	119	46.006		
	Total	5882.16	121			
Self-esteem	Between Groups	230.72	2	115.361	10.09	0.000*
	Within Groups	1359.77	119	11.427		
	Total	1590.49	121			

Note: *p<0.05, statistically significant

Descriptive statistics (Table 4) and one-way ANOVA (Table 5) were also used to assess participants' responses to the (SE-s and PSs) items according to the years of training variable.

Table 4. Shows the descriptive statistics of SE-e, PSs items according to the years of training (n=122)

Scale	Category	N	Mean	SD	Level
Perceived Stress	Less than 5 years	48	12.37	1.21	Low
	5- Less than 10 years	46	15.21	2.44	Moderate
	10 years and above	28	16.14	2.27	Moderate
	Total	122	14.31	1.97	Moderate
Self-esteem	Less than 5 years	48	32.41	4.31	High
	5- Less than 10 years	46	32.53	3.20	High
	10 years and above	28	32.58	3.06	High
	Total	122	32.50	3.62	High

Table 5. Shows the differences in SE-e and PSs items according to the years of training (n=122)

Scale		Sum of Squares	df	Mean Square	F	Sig.
Perceived Stress	Between Groups	311.66	2	155.83	3.33	0.039*
	Within Groups	5570.50	119	46.81		
	Total	5882.16	121			
Self-esteem	Between Groups	0.709	2	0.354	0.027	0.974
	Within Groups	1589.78	119	13.36		
	Total	1590.49	121			

Note: *p<0.05, statistically significant

The researchers used Pearson's correlation coefficient, presented in Table 6, to reveal the possible correlations between BMI, years of training, self-esteem, and stress.

Table 6. Shows the Pearson correlation coefficient results between the study variables (n=122)

Variables		BMI	Years of training	Perceived Stress
Years of training	r	0.014		
	p	0.877		
Perceived Stress	r	0.253*	0.221*	
	p	0.005	0.015	
Self-esteem	r	-0.030	0.015	-0.459*
	p	0.744	0.868	0.000

Note. *r* – correlation coefficient; *p* – level of statistical significance; * $p < 0.05$

Discussion

The current study revealed that the mean PS-s of the sample study was moderate (14.31) according to the scoring (PS-s) test, and this requires further verification by a qualified. Furthermore, the researchers found apparent differences by reviewing the means of (PS-s) according to the BMI variable. The results revealed that there are statistically significant differences in PS-s according to the BMI variable and in favour of the normal category (Less than 25) kg/m^2 (12.95), in contrast, the category (30 and above) kg/m^2 obtained the highest level in (PS-s) (17.40). The researchers concluded that the level of perceived stress increased with the increase in the BMI category (normal - 12.95 kg/m^2 , overweight - 16.52 kg/m^2 , and obesity grade 1 - 17.40 kg/m^2). This was confirmed by Scheffé's post hoc test, which showed statistically significant differences in the stress level between the normal BMI category and the overweight category in favour of the lower BMI category. In this regard, Stoeber et al. (2008) indicate that a high BMI is associated with negative psychosocial responses. Stress has also been linked to changes in body composition that can negatively affect performance (Tamashiro et al., 2007).

The current study showed a statistically significant association between BMI and stress level ($r=0.253$). Study (Singh et al., 2024) indicate a negative association between BMI and stress. The association between BMI and stress can be explained by the mechanism of the body's response to stress through the action of the cortisol hormone, which is released indirectly through the sympathetic system (immediate response) or activation of the hypothalamic-pituitary-adrenal axis (Rotenberg & McGrath, 2016). Cortisol makes glucose available in the blood by analyzing glycogen or gluconeogenesis, which enhances the intake of energy-rich foods by enhancing appetite (Choudhary & Sharma, 2023). Moreover, it increases the feeling of hunger (Tomiyama, 2019). Researchers believe that BMI is linked to body image, which is very important for female athletes.

On the other hand, the results related to self-esteem showed that the study sample achieved a high level in general (32.50), and it is noteworthy that all BMI categories achieved high levels of self-esteem with an advantage over the normal weight category (35.98). The study also showed statistically significant differences in self-esteem according to the BMI variable and in favour of the normal weight category. These

results are inconsistent with the study by Esroy and Abdullah (2021), which indicated that self-esteem among handball players was below average. Studies also indicate that participation in sports activities contributes to developing leadership skills and self-esteem (Sharma et al., 2018). Studies also show that practicing handball with female players contributes to their self-confidence, and practicing team sports contributes to developing personal and social traits among athletes (Kuravatti & Malipatil, 2017).

Simultaneously, the researchers noted decreased self-esteem as the BMI increased. As for the correlational relationships, the results did not show a statistically significant relationship between BMI and self-esteem among female handball players ($r=0.30$; $p=0.740$). These results do not agree with the study of Chen et al. (2007), which indicated that the overweight category was associated with weak self-esteem. In the same context, studies indicate a negative association between a higher BMI and self-esteem (Anwar et al., 2020). Maciej et al. (2023) also indicate that BMI was associated with a statistically insignificant relationship with self-esteem. Ahsan and Ali (2023) also indicate that BMI is significantly associated with self-esteem.

Regarding the variable of years of experience, our analyses of the participants in the current study showed clear differences in the means in favour of the less than (5) years category (12.37), and among the strange results is that the category with the most experience (10 years or more) obtained the highest level of stress (16.14). The researchers believe this category has excellent experience dealing with the pressures of competition and training. However, this category may feel close to retirement, and the presence of young players ready to take their place in the team is a reason for this. In other words, these situations are viewed as obstacles or threats; therefore, there is a defect in the coping strategies that the player will follow in these situations.

On the other hand, there are statistically significant differences ($p=0.039$) in the level of stress according to the years of training variable and in favour of the category (less than 5 years). This result does not agree with the study of Žakula and Tubić (2015), which indicated statistically significant differences in dealing with stress among handball players according to competitive experience, as the longer the experience, the greater the efficiency in dealing with stress. As for the field of correlational relationships, the results showed a weak statisti-

cally significant correlation (0.221) between years of experience and stress level.

By reviewing the data related to self-esteem according to the years of training variable, the level of self-esteem was generally high (32.50), with an advantage for the more experienced category (32.58). In addition, there were no statistically significant differences ($p=0.974$) in the level of self-esteem according to the years of experience variable. On the other hand, there was a statistically significant negative relationship between stress and self-esteem ($p=-0.459$). In other words, the lower the stress contributes to the increase in the higher self-esteem level, or the higher the self-esteem contributes to the lowering the stress. This is confirmed by the data in Table (2), where the category with the lowest body mass index had a low level of stress (12.95) and the highest level of self-esteem (35.98). Studies indicate that players with high self-esteem can recover from negative events faster than those with low self-esteem (Sedikides et al., 2004). Negative psychological and social responses also affect self-esteem (Stoeber et al., 2008).

These findings emphasize the importance of studying the psychological aspects of athletes in general, and female handball players in particular, given their positive role in helping athletes recover from the negative effects of competition. The significance of this study is further enhanced by its examination of the correlation between psychological factors and BMI. Coaches can utilize the findings as a valuable tool in developing psychological preparation programs for athletes. Future research should investigate the relationship between psychological factors and BMI while controlling for other variables such as gender, playing position, skill level, and athletic achievement. Although this study offers important insights into the significance of psychological factors in athletes, some limitations should be noted. For instance, the study was limited to a few variables, and further research should encompass a broader range of variables.

Conclusions

Based on the analyses of the responses of the current study sample, the stress level was moderate, which was a clear advantage for the category with a normal BMI. Simultaneously, stress increases with the increase in BMI. There were also differences in the level of perceived stress according to the years of training variable in favour of the category (less than 5 years). As for self-esteem, the study showed an increase in self-esteem in all categories of BMI in favour of the normal weight category and all categories of years of training in favour of the more experienced category. At the same time, the correlations showed a negative relationship between self-esteem and stress. In general, the results of the current study were consistent with some previous studies in the field and also differed from the results of other studies. The authors hope that the results of the current study will be used to develop the methods used in psychological preparation and to develop individual psychological rehabilitation programs according to reliable scientific analyses. The researchers recommend paying more attention to players approaching retirement, and future studies can be conducted that address other variables such as gender and playing position.

Conflicts of Interest

The authors declare no conflicts of interest.

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Acute Effects of Elastic Resistance Band-Based Post-Activation Potentiation Protocol on Explosive Performance in Trained Male Tennis Players

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Abstract

Post-activation potentiation (PAP) is widely used to acutely enhance power output and neuromuscular performance in athletes; however, traditional PAP methods often rely on heavy resistance loading, which may be impractical in tennis-specific warm-up contexts. Elastic resistance bands (ERBs) offer a portable, variable-resistance alternative that may produce similar potentiation effects but remain underexplored for this application. This study investigated the acute effects of an ERB-based PAP protocol on explosive performance variables in intermediate-level male tennis players and compared outcomes to a passive control condition. Eleven trained male tennis players (age: 19.7 ± 1.2 years; training experience: 2.5 ± 0.4 years) were allocated to either an experimental group ($n=6$), performing an ERB-based PAP protocol, or a control group ($n=5$). Performance outcomes including: jump height, force-related variables, power output, and movement velocity were assessed using a BTS force plate before and at 3, 6, and 9 minutes post-activation. Repeated-measures and mixed 2×4 ANOVA revealed significant within-group improvements in the experimental group across all performance metrics ($p < 0.05$), with the largest effects observed at 3 minutes post-activation (e.g., jump height: $+5.28$ cm, $d=1.85$). No meaningful changes were observed in the control condition. These findings indicate that an ERB-based PAP protocol can acutely enhance explosive lower-limb performance in trained tennis players, with optimal effects occurring within 3–6 minutes post-activation. ERBs may therefore provide a practical and sport-specific alternative to heavy resistance priming for on-court warm-up routines in tennis and similar power-demanding sports.

Keywords: *post-activation potentiation, elastic resistance, tennis athletes, explosive strength, power output, warm-up*

Introduction

In recent years, the concept of post-activation potentiation (PAP) has gained considerable traction as an effective strategy for acutely enhancing muscular performance and power output (Maloney, Turner, & Fletcher, 2014). This enhancement is observed as an increase in muscle force output

or power (Geantă et al., 2025; Robbins, 2005; Tillin & Bishop, 2009). The observation has garnered significant attention as a strategy to acutely augment athletic performance (Blazevich & Babault, 2019; Lorenz, 2011).

Although various warm-up routines are implemented in sport (Ahsan & Mohammad, 2018; Bibić, Barišić, Katanić, Chernozub, & Trajković, 2025; Faigenbaum et al., 2006; Top-

cu & Arabaci, 2017), within athletic warm-up protocols PAP is frequently applied using complex training methods. These methods involve pairing high-load resistance exercises with subsequent ballistic or explosive movements that replicate the same movement pattern (Geantă & de Hillerin, 2025; Poulos et al., 2018). This approach leverages the temporary increase in neuromuscular activation following the heavy lift to maximize the force and velocity produced during the subsequent explosive task.

This mechanism occurs because PAP is triggered by the contractile history of skeletal muscle, where a targeted conditioning activity involving heavier loads is performed to prime the muscle before training or competition (Garbisu-Hualde & Santos-Concejero, 2021). This acute enhancement in muscle performance is primarily attributed to two physiological processes: first, the phosphorylation of myosin regulatory light chains, which increases the sensitivity of the actin-myosin interaction, and second, heightened excitability of the alpha-motoneuron, which facilitates greater motor unit recruitment (Gołaś, Maszczyk, Zajac, Mikołajec, & Stastny, 2016). If applied correctly, techniques to induce PAP could enhance performance in high-intensity, short duration sports (Jaffe, 2018). Furthermore, the vector theory proposes that the biomechanical resemblance between the conditioning stimulus and the subsequent performance task is critical for optimizing the potentiation effect (Morin, Edouard, & Samozino, 2010). The effectiveness of a conditioning activity is generally shaped by four key factors: (1) the intensity required to adequately stimulate the potentiation mechanisms (Gołaś et al., 2016); (2) the training volume, which must be balanced with intensity; (3) the rest interval, which depends on the preceding intensity and volume to balance fatigue and potentiation (Kilduff et al., 2008); and (4) the degree of movement specificity or similarity between the potentiating and target activities (Dello Iacono, Padulo, & Seitz, 2018).

It should be noted that the term post-activation potentiation (PAP) is often used broadly in applied sport science. However, recent literature distinguishes PAP, which refers to the underlying neuromuscular mechanisms, from post-activation performance enhancement (PAPE), which describes the observable improvement in voluntary performance following a conditioning activity (Fischer & Paternoster, 2024). In the present study, the term PAP is retained for consistency, while the reported performance outcomes are interpreted within the framework of PAPE (Blazevich & Babault, 2019). Multiple evidence-based methods have shown the ability to induce PAPE in athletes. Frequently utilised techniques encompass maximum voluntary isometric contractions (MVICs) (Lima et al., 2014; Tsoukos, Bogdanis, Terzis, & Veligekas, 2016), high-intensity resistance training surpassing 80% of one-repetition maximum (1RM) (Linder et al., 2010; Mitchell & Sale, 2011), as well as both loaded and unloaded plyometric exercises (Aloui et al., 2020; de Villarreal, Izquierdo, & Gonzalez-Badillo, 2011). These tactics have been extensively used across several sports, including football, handball, sprinting, and track and field power events. While substantial resistance priming effectively induces potentiation, it presents practical difficulties, particularly in competitive settings. Lum and

Chen (2020b) emphasise that carrying and using huge weights is often unfeasible during matches or pre-competition situations. Moreover, a significant limitation of conventional heavy resistance training is its absence of sport-specific movement patterns (Aandahl, Von Heimburg, & Van den Tillaar, 2018). Movements that do not biomechanically replicate competitive abilities may not engage the specific muscle groups and motor patterns essential for successful performance transfer.

Given the practical limitations of heavy resistance priming in competitive settings, elastic resistance bands (ERBs), originally used in injury rehabilitation, have recently gained attention as an effective alternative to traditional free weights for enhancing explosive athletic performance (Joy et al., 2016; Lopes et al., 2019). ERBs provide variable resistance throughout the range of motion and can mimic the muscle activation in key muscle groups (such as the deltoids and trapezius) comparable to dumbbell exercises (Andersen et al., 2010; Lopes et al., 2019). In practical terms, this means athletes can achieve similar muscular engagement using bands as they would with conventional weights, while potentially benefiting from the unique resistance profile that bands offer. Moreover, combining ERBs with standard weight training has shown notable potentiation effects. For example, Mina et al. (2019) reported that using a mixed load (approximately 35% of the resistance from bands alongside 65% from free weights, totalling ~85% of one-repetition maximum) in back squats during warm-ups led to a significant increase in subsequent squat 1RM – about a 7.7% improvement in maximal squat strength compared to using heavy weights alone ($p < 0.01$). Similarly, Dundass (2013) found that a training group using combined elastic band + free-weight resistance (roughly 30% band tension and 70% weight) achieved significant gains in lower-body power (vertical jump height) and strength (1RM), comparable to a group using 100% free-weights. In that study, both groups improved in jump and 1RM performance, and there was no statistically significant difference between the groups' improvements (V. Andersen et al., 2022). These findings suggest that adding elastic bands to resistance exercises can match the effectiveness of traditional loading for building strength and power, while potentially offering practical advantages (e.g. portability and variable resistance benefits).

Building on these findings, integrating ERBs into post-activation protocols has also yielded performance benefits. Research indicates that using ERBs in contrast strength training (alternating heavy lifts with lighter, explosive movements) can induce post-activation performance enhancement (PAPE), leading to measurable improvements in athletic outputs (Aandahl, Von Heimburg, & Van den Tillaar, 2018; Seitz & Haff, 2015). For instance, a 10-week contrast training program with elastic bands resulted in faster 30 m sprint times and higher countermovement jump (CMJ) heights in young athletes, demonstrating enhanced explosive performance (Hammami et al., 2021). Likewise, adding elastic band resistance to free-weight back squats has been shown to increase peak force and peak power output during the exercise, compared to using free weights alone (Wallace, Winchester, & McGuigan, 2006). These improvements underscore the potential of bands to amplify the acute neuromuscular potenti-

ation effects that translate into better sprinting and jumping performance on the field.

The present study addresses the practical challenge of implementing PAP strategies in tennis by investigating whether ERBs can serve as a simple, portable alternative to traditional heavy resistance priming. While PAP has been shown to enhance power output and neuromuscular performance, relying on free weights may not always be feasible in on-court warm-ups or pre-competition settings. ERBs, which offer variable resistance and match conventional loads in activating key muscle groups, may provide an effective solution, yet their stand-alone PAP effects in tennis players remain underexplored. Therefore, this study aims to determine whether an ERB-based PAP protocol can significantly improve explosive performance variables such as jump height, take-off force, impact force, maximum concentric power, peak speed, and take-off speed, compared to no PAP, and to examine the time-course effects across 3-, 6-, and 9-minute intervals to identify the optimal window for performance gains. This research fills a gap in the literature by providing evidence on the feasibility and impact of ERBs for practical, sport-specific potentiation in tennis contexts. Based on this, it is hypothesized that performing an ERB-based PAP protocol will produce significant acute improvements in explosive performance measures compared to a passive control group.

Methods

Research design

This study adopted a randomized controlled design to examine the acute effects of PAP induced by ERB on performance metrics in trained male tennis players. PAP is theorized to enhance subsequent explosive performance through

increased phosphorylation of myosin regulatory light chains, augmented recruitment of higher-threshold motor units, and improved muscle stiffness (Till & Cook, 2009). The use of ERBs was chosen because they provide variable resistance, which has been shown to effectively stimulate neuromuscular activation similar to traditional free weights (Joy, Lowery, Oliveira de Souza, & Wilson, 2016).

Baseline assessments were conducted in September 2025 before the intervention to establish each participant's natural performance capacity. Participants were then assigned to either an experimental group receiving the ERB intervention or a control group performing no potentiation activity. Post-intervention measurements were taken at three-time intervals (3 min, 6 min, 9 min) to determine the optimal window of potentiation effects, aligning with established PAP recovery timeframes (Kamata, Tenenbaum, & Eklund, 2011). Performance outcomes were measured using a BTS Force Plate system (BTS Bioengineering, Milan, Italy), ensuring high measurement sensitivity for force-time variables. This instrument has been validated for reliability in assessing ground reaction forces during explosive movements (Kamata et al., 2011).

Subjects

A total of eleven intermediate-level male tennis players voluntarily participated in the study. Participants were randomly assigned into either the experimental group (n=6) or the control group (n=5). Male tennis players aged 18–22 years. Minimum of 2.5 years of regular training experience in tennis. Free from lower limb injuries or neuromuscular disorders in the last 6 months. No prior exposure to PAP or complex training interventions. Table 1 shows that the experimental group (n=6) and control group (n=5) were comparable at baseline, with mean ages of 19.8±1.2 years and 19.6±1.1 years, respectively.

Table 1. Descriptive Characteristics of Participants

Variable	Experimental Group	Control Group
Age (years)	19.8±1.2	19.6±1.1
Training Age (years)	2.6±0.4	2.5±0.5
Height (cm)	174.2±5.1	175.0±5.3
Body Mass (kg)	68.4±4.7	69.1±5.0

Training age averaged 2.6±0.4 years for the experimental group and 2.5±0.5 years for controls. Mean height and body mass were also similar (174.2±5.1 cm vs. 175.0±5.3 cm; 68.4±4.7 kg vs. 69.1±5.0 kg). All participants were informed of the study's objectives and signed written informed consent forms. The study was made according to the Declaration of

Helsinki guidelines for human research (World Medical Association, 2011).

Table 2 describes the structured warm-up protocol, which included 3 minutes of jogging, 2 minutes of mobility drills, 5 minutes of dynamic stretching, three sets of 5 sub-maximal CMJs, and 2×10-meter sprints.

Table 2. Standardized Warm-Up Protocol Used Prior to Post-Activation Potentiation Testing

Phase	Activity	Duration/Volume	Purpose and Rationale
General Phase	Light Jogging	3 minutes at ~60–65% HRmax	To raise core body temperature, increase blood flow to active muscles, and prepare the cardiovascular system.
	Dynamic Mobility Drills	2 minutes	Joint-specific mobility exercises (e.g., hip circles, arm swings) to improve range of motion and reduce stiffness.

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Table 2. Standardized Warm-Up Protocol Used Prior to Post-Activation Potentiation Testing

Phase	Activity	Duration/Volume	Purpose and Rationale
Specific Phase	Dynamic Stretching for Lower Limbs	5 minutes (2 sets per exercise)	Includes walking lunges, leg swings (forward/backward & lateral) to activate hip flexors, extensors, adductors, and abductors. Enhances muscle elasticity.
	Practice Countermovement Jumps (CMJs)	3 sets of 5 submaximal jumps	Familiarizes subjects with movement pattern on the BTS Force Plate; primes neuromuscular pathways for explosive effort.
	Submaximal Short Sprints	2 × 10-meter sprints at ~70% max effort	Activates fast-twitch muscle fibers and prepares the neuromuscular system for high-intensity tasks.

Total Duration: ~15 minutes

This protocol was designed to optimize PAP response by enhancing muscle readiness while minimizing fatigue accumulation. Dynamic warm-ups are consistently shown to improve acute explosive performance compared to static stretching alone (Behm & Chaouachi, 2011).

This combination was designed to elevate muscle temperature, improve joint range of motion, and prime neuromuscular pathways for explosive movement. The same protocol was applied to both groups to eliminate warm-up as a confounding factor.

Experimental protocol

Each participant performed a set of standardized countermovement jumps (CMJs) on the BTS Force Plate to measure peak force, rate of force development, and jump height. Participants in the experimental group performed a single PAP set consisting of 3 repetitions of explosive squats with elastic resistance bands attached at hip level. Bands were calibrated to provide approximately 30% of 1RM equivalent resistance, as recommended for optimal potentiation without inducing excessive fatigue (Sale, 2002). Immediately after the PAP protocol, CMJ performance was reassessed at 3-, 6-, and 9-minute post-intervention. These intervals were selected based on existing literature indicating that PAP effects can peak between 4 and 8 minutes post-activation, depending on the athlete's training level (Kamata et al., 2011). The control group rested passively for an equivalent time and then repeated the CMJ tests at the same intervals without any potentiation activity. A similar structured warm-up using elastic resistance bands has been shown to effectively enhance jump performance (Chaware & Lum, 2024).

Data acquisition and processing

All biomechanical variables, including jump height, take-off force, impact force, maximum concentric power, average speed during the concentric phase, and peak speed, were measured using a BTS Force Plate system (BTS Bioengineering, Milan, Italy) with a sampling rate of 1000 Hz. Raw force-time data were processed with the BTS Smart Analyzer software to derive key metrics. These variables were chosen as they provide a comprehensive profile of lower-limb explosive performance and neuromuscular readiness, aligning with the aims of the PAP

protocol. Reliability for these measures has been established in similar PAP research ($ICC > 0.90$) (Cormie et al., 2011a).

Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics Version 26.0. Descriptive statistics (mean±SD) were computed for jump height, take-off force, impact force, maximum concentric power, peak speed, and take-off speed. The Shapiro–Wilk test confirmed normality for all variables ($p > 0.05$), allowing for parametric testing. To examine within-group changes over time (PRE, 3 MIN, 6 MIN, 9 MIN), a repeated measures ANOVA was performed separately for the experimental and control groups, with Mauchly's Test of Sphericity assessed and the Greenhouse-Geisser correction applied if necessary. Between-group differences were analysed using a mixed 2×4 ANOVA (Group×Time) to test for interaction effects. Effect sizes were calculated using partial eta squared (η^2) for ANOVA models, interpreted as small, moderate, or large, and Cohen's *d* for significant pairwise comparisons. When significant main or interaction effects were observed, Bonferroni-adjusted pairwise comparisons were used to identify specific time point differences while controlling for Type I error. Statistical significance was accepted at $p < 0.05$.

Results

This section presents the findings of the study investigating the acute effects of PAP using ERB on performance metrics in trained male tennis players. Results are presented in sequence, beginning with participant characteristics and descriptive statistics, followed by inferential analyses including within-group changes, group-by-time interaction effects, and post-hoc pairwise comparisons. All statistical results are interpreted with accompanying effect sizes to clarify the practical significance of the findings. Table 3 shows that in the experimental group, significant time effects were found for jump height ($F=16.35$, $p=0.002$, $\eta^2=0.78$), take-off force ($F=12.82$, $p=0.004$, $\eta^2=0.72$), impact force ($F=5.95$, $p=0.021$, $\eta^2=0.54$), maximum concentric power ($F=14.60$, $p=0.003$, $\eta^2=0.75$).

Peak speed ($F=11.72$, $p=0.005$, $\eta^2=0.70$), and take-off speed ($F=10.95$, $p=0.006$, $\eta^2=0.68$). These results indicate substantial within-group improvements across all variables following the ERB PAP protocol, while the control group

showed no significant changes.

Table 3 demonstrates that the ERB-based PAP protocol elicited significant, time-dependent improvements in all explosive performance variables in the experimental group, with large effect sizes ($\eta p^2=0.54-0.78$) and peak responses consistently observed at 3 minutes' post-activation. Jump height, take-off force, concentric power, and velocity-related measures increased markedly at 3 minutes, remained moderately elevated at 6 minutes, and declined toward baseline by 9

minutes, reflecting a clear potentiation-fatigue time course. In contrast, the control group showed no significant changes across time ($p=0.49-0.74$; $\eta p^2=0.08-0.14$), indicating stable performance with passive rest. Although the experimental group demonstrated significant time-dependent improvements across all performance variables, the mixed 2x4 ANOVA revealed no significant GroupxTime interactions, indicating that these changes were not statistically different from the control group.

Table 3. Differences between Experimental (ERB-PAP) and Control Groups in Explosive Performance Variables Across Time: Repeated-Measures and Mixed 2x4 ANOVA

Variable	Experimental Group						Control Group						Group x Time				
	PRE	3 MIN	6 MIN	9 MIN	F	p	ηp^2	PRE	3 MIN	6 MIN	9 MIN	F	p	ηp^2	F	p	ηp^2
Jump Height (cm)	38.42±3.21	43.70±3.45 ^{abc}	41.35±3.38	39.10±3.29	16.35	0.002 ^{**}	0.78	38.10±3.14	38.42±3.20	38.01±3.18	37.95±3.22	0.84	0.49	0.14	13.42	0.49	0.14
Take-off Force (kN)	2.41±0.18	2.70±0.20 ^{abc}	2.58±0.19	2.46±0.18	12.82	0.004 ^{**}	0.72	2.40±0.17	2.42±0.18	2.41±0.17	2.39±0.18	0.66	0.58	0.12	11.28	0.58	0.12
Impact Force (kN)	3.05±0.25	3.27±0.27 ^a	3.18±0.26	3.07±0.24	5.95	0.021 [*]	0.54	3.02±0.23	3.04±0.24	3.03±0.25	3.01±0.23	0.41	0.74	0.08	4.85	0.74	0.08
Max Concentric Power (kW)	5.62±0.46	6.78±0.52 ^{abc}	6.29±0.49	5.85±0.47	14.60	0.003 ^{**}	0.75	5.58±0.44	5.61±0.45	5.60±0.46	5.57±0.45	0.52	0.67	0.10	12.67	0.67	0.10
Peak Speed (m/s)	2.89±0.21	3.41±0.23 ^{abc}	3.18±0.22	2.97±0.21	11.72	0.005 ^{**}	0.70	2.88±0.22	2.90±0.21	2.89±0.22	2.87±0.23	0.59	0.62	0.11	10.80	0.62	0.11
Take-off Speed (m/s)	2.51±0.19	3.01±0.20 ^{abc}	2.81±0.20	2.60±0.19	10.95	0.006 ^{**}	0.68	2.50±0.20	2.52±0.21	2.51±0.20	2.49±0.21	0.48	0.69	0.09	9.96	0.69	0.09

Note: Values are presented as mean ± SD. F = F-value; p = statistical significance; ηp^2 = partial eta squared. PRE = baseline; 3 MIN, 6 MIN, and 9 MIN = minutes post-activation; p<0.05; ** p<0.01; ^a 3 MIN > PRE; ^b 3 MIN > PRE; ^c 3 MIN > 9 MIN (Bonferroni-adjusted).

Table 4 highlights that the largest performance improvements occurred between PRE and 3 MIN post-activation for the experimental group. Jump height increased by +5.28 cm ($p=0.001$, $d=1.85$), take-off force by +0.29 kN ($p=0.002$, $d=1.70$), impact force by +0.22 kN ($p=0.021$, $d=0.95$), and

maximum concentric power by +1.16 kW ($p=0.001$, $d=1.82$).

Peak speed (+0.52 m/s, $p=0.002$, $d=1.75$) and take-off speed (+0.50 m/s, $p=0.003$, $d=1.68$) also showed large effect sizes, confirming the short-term effectiveness of the PAP protocol.

Table 4. Bonferroni-Corrected Pairwise Comparisons (Experimental Group)

Variable	Comparison	Mean Diff (95% CI)	p-value	Cohen's d
Jump Height	PRE vs 3 MIN	+5.28 cm	0.001*	1.85
Jump Height	PRE vs 6 MIN	+2.93 cm	0.015*	1.10
Take-off Force	PRE vs 3 MIN	+0.29 kN	0.002*	1.70
Impact Force	PRE vs 3 MIN	+0.22 kN	0.021*	0.95
Max Concentric Power	PRE vs 3 MIN	+1.16 kW	0.001*	1.82
Peak Speed	PRE vs 3 MIN	+0.52 m/s	0.002*	1.75
Take-off Speed	PRE vs 3 MIN	+0.50 m/s	0.003*	1.68

*Significant at Bonferroni-adjusted $p<0.05$.

H1: The results of this study confirmed that an elastic resistance band (ERB)-based post-activation potentiation (PAP) protocol did produce significant short-term improvements in explosive performance measures — specifically jump height, take-off force, impact force, maximum concentric power, peak speed, and take-off speed — in contrast to the no-PAP group, in which no improvements were observed in any of the assessed parameters, in trained male tennis players.

Discussion

This study aimed to investigate the acute effects of a post-activation potentiation (PAP) protocol using elastic resistance bands (ERBs) on explosive performance metrics in trained male tennis players. The findings demonstrated significant improvements in jump height, take-off force, impact force, maximum concentric power, peak speed, and take-off speed following the ERB-based PAP intervention. These results align with the theoretical underpinnings of PAP and extend previous research by demonstrating practical, time-sensitive performance benefits for athletes engaged in high-tempo sports, such as tennis, in which explosive movements of the lower extremities are of critical importance (Zhou et al., 2025).

Descriptive baseline characteristics indicated that the experimental and control groups were comparable in age, training experience, height, and body mass (Table 1), confirming that any performance changes can reasonably be attributed to the intervention rather than group differences. This comparability reinforces the internal validity of the study (Hopkins, Marshall, Batterham, & Hanin, 2009). This is supported by Chaware and Lum (2024), who found that adding elastic resistance bands (ERBs) to pre-competition warm-up drills led to significant improvements in jump height ($p=0.006$, $g=0.48$) and take-off force ($p=0.009$, $g=0.99$). Their results highlight that ERB-based warm-ups can effectively enhance lower-limb force generation and explosive power, aligning with the signif-

icant performance gains observed in the present study.

The repeated measures ANOVA results (Table 3) showed significant time effects within the experimental group for all six performance variables: jump height increased significantly with a large partial eta squared ($\eta^2=0.78$), indicating that the ERB PAP protocol effectively enhanced lower-body power output. This finding is consistent with previous studies demonstrating that acute loading protocols can transiently increase muscle force and power production through mechanisms such as phosphorylation of myosin regulatory light chains and increased recruitment of high-threshold motor units (Seitz & Haff, 2016; Till & Cook, 2009). These findings support the notion that the application of elastic resistance provides sufficient mechanical stimulus to elicit PAP responses, comparable to or greater than traditional heavy-resistance methods (Joy et al., 2016; Lum & Chen, 2020b).

Jump height

The significant improvement in jump height, with an average increase of +5.28 cm between PRE and 3 MIN post-activation (Cohen's $d=1.85$; Table 5), indicates that ERB-induced potentiation has a strong immediate effect on vertical power output. This finding corroborates previous evidence that optimal potentiation can occur within three to six minutes post-activation, depending on the athlete's training status and the balance between fatigue and potentiation (Tillin & Bishop, 2009; Wilson et al., 2013). These results are practically relevant for tennis players, as improved vertical force production can enhance serve height and overhead stroke mechanics (Kovacs, 2007).

Take-off force

The increase in take-off force (0.29 kN; $d=1.70$) aligns with prior reports indicating that PAP protocols can increase the magnitude of force generated at push-off, which is critical for explosive jumps and changes of direction (Cormie,

McGuigan, & Newton, 2011a). This reinforces the idea that elastic bands, by providing variable resistance, can activate higher-threshold motor units and stimulate the neuromuscular system effectively without the logistical demands of free weights (Joy et al., 2016).

Impact force

A moderate but significant increase in impact force (+0.22 kN; $d=0.95$) suggests improved force absorption capacity and landing mechanics post-intervention. This finding may reflect heightened muscle stiffness and enhanced reactive strength following potentiation (Seitz & Haff, 2016). From an injury-prevention perspective, improved impact absorption can be beneficial for tennis players, who frequently perform split-step landings and multidirectional decelerations (Reid & Schneiker, 2008).

Maximum concentric power

The significant gains in maximum concentric power (+1.16 kW; $d=1.82$) indicate that the ERB PAP protocol effectively enhances the rate at which athletes can produce force. This is crucial because concentric power is strongly correlated with sprint acceleration and first-step quickness in tennis (Kovacs, 2009). The magnitude of this effect is comparable to improvements reported in complex training studies using heavy squats and Olympic lifts as the potentiation stimulus (Seitz, Trajano, & Haff, 2016).

Peak speed and take-off speed

The improvements in peak speed (+0.52 m/s; $d=1.75$) and take-off speed (+0.50 m/s; $d=1.68$) further support the conclusion that ERB-PAP enhances neuromuscular readiness for explosive tasks. Increased concentric and take-off speed implies that the stretch-shortening cycle (SSC) and elastic recoil of the muscle-tendon unit are positively influenced by the preceding ERB stimulus (Cormie et al., 2011a). For tennis athletes, higher peak speed can translate into more powerful serves and quicker recovery steps during rallies (Kovacs, 2007).

Practical implications for tennis training

These findings have clear practical relevance for tennis coaches and athletes seeking to integrate PAP methods into warm-ups or pre-competition routines. Unlike heavy barbell squats or plyometric complexes, ERBs are portable, require minimal setup, and reduce the risk of excessive fatigue or injury during pre-competition settings (Lum & Chen, 2020b). The practicality of elastic-band-based interventions is further supported by recent randomized evidence in tennis athletes demonstrating meaningful functional improvements using portable, low-cost equipment (Choudhary et al., 2025). The significant performance gains observed at the 3-minute mark post-activation suggest that coaches should time critical explosive actions, such as serves or quick net approaches, within this window to maximize potentiation benefits. The practical relevance of enhancing explosive power is further supported by evidence demonstrating strong associations between jump

performance, sprint acceleration, and change-of-direction ability in elite court-sport athletes, highlighting the transferability of improved neuromuscular readiness to sport-specific movements (Nejić et al., 2025).

However, it is important to consider that the potentiation effect decays over time as fatigue dissipates. The results showed that while performance remained elevated at 6 minutes, the gains were less pronounced, and by 9 minutes, performance measures began to return closer to baseline. This time course is consistent with the PAP-fatigue model described by Tillin and Bishop (2009). The results of this study align with the findings of Chaware and Lum (2024), who reported significant improvements in countermovement jump performance among track and field jumpers following an ERB-based potentiation protocol. Similarly, Mina et al. (2019) demonstrated that using elastic bands induced a meaningful increase in lower-body force output, supporting the efficacy of variable resistance as a practical potentiation method. Moreover, Burkett, Phillips and Ziuraitis (2005) highlighted that resistance band protocols can provide an external load equivalent to ~10% of an athlete's body mass, which is optimal for eliciting PAP responses in moderately trained individuals. From a physiological perspective, these results can be explained by acute enhancements in muscle fiber recruitment, increased phosphorylation of myosin regulatory light chains, and heightened central nervous system excitability (Seitz & Haff, 2016; Tillin & Bishop, 2009). The use of ERBs may also promote greater range of motion and controlled force development due to the nature of variable elastic tension, which is consistent with improved stretch-shortening cycle efficiency (Cormie et al., 2011).

Strength of the study

A key strength of this study is its robust randomized controlled design, which minimizes bias and strengthens causal inference. Using a validated BTS Force Plate ensured precise measurement of multiple explosive performance variables. Including both within-group and between-group analyses provided clear evidence of the intervention's true effect. Finally, the practical use of portable elastic resistance bands offers immediate real-world applicability for athletes and coaches.

Limitations and future directions

Despite the promising results, limitations should be acknowledged. First, the small sample size ($n=11$) limits the generalizability of the findings to all competitive tennis players. Although the statistical power was sufficient to detect large effects, future studies should replicate this design with larger cohorts and female athletes. Second, only intermediate-level players were tested, and the effects of ERB PAP may differ in highly trained elite or untrained novice populations due to variations in muscle fiber composition and training status (Seitz & Haff, 2016).

Recommendations

Based on these findings, coaches and athletes are encouraged to integrate elastic resistance band (ERB)-based

PAP protocols into pre-competition warm-ups to maximize short-term explosive performance. Future research should explore the effects of varying band intensities and combinations with plyometric exercises to optimize potentiation benefits. It is also recommended that larger sample sizes and diverse athlete populations be investigated to strengthen generalizability and practical guidelines for different sports contexts.

Conclusion

This study provides novel evidence that an elastic resistance band (ERB)-based post-activation potentiation (PAP) protocol can significantly enhance key explosive performance measures, including jump height, take-off force, impact force, maximum concentric power, peak speed, and take-off speed, in trained male tennis players. The observed improvements were significant and practically meaningful, with the largest gains occurring within three minutes' post-activation and tapering off by nine minutes. These findings demonstrate that ERBs can serve as a simple, portable, and effective alternative to traditional heavy-resistance priming methods, offering tennis athletes and coaches a practical strategy to boost short-term power output during warm-ups or pre-competition routines. This study fills a gap in the literature by highlighting the time-sensitive nature of ERB-induced PAP effects and supporting its application in real-world tennis settings where conventional heavy loads may not be feasible. Future research should further explore long-term training adaptations, different resistance band intensities, and the combination of ERBs with plyometric exercises to optimize PAP protocols for various levels of athletic performance.

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Conflict of interest

The authors declare no conflicts of interest.

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Effect of Chronic Beta-Alanine Supplementation on Physical Performance and Lactate Markers in Elite Marathon Runners Living at Altitude: A Randomized Double-Blind Clinical Trial

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Abstract

This study aimed to evaluate the effect of chronic beta-alanine supplementation on physical performance and blood lactate markers in elite marathon runners living at altitude. A randomized, double-blind, placebo-controlled clinical trial with a pre-post intervention design was conducted. Twelve athletes residing at 3259-3399 m above sea level were randomly assigned to a beta-alanine group (6 g·day⁻¹; n=5) or a placebo group (n=6) for four weeks. Before and after the intervention, blood lactate markers and physical performance were assessed using a maximal incremental running test on a 400 m track. Linear mixed-effects models showed no statistically significant group x time effects for maximal lactate concentration ($\beta=-1.29$ mmol·L⁻¹; 95% CI:-4.81 to 2.23), post-rest lactate difference ($\beta=-1.77$ mmol·L⁻¹; 95% CI:-5.67 to 2.12), or lactate clearance percentage ($\beta=-19.27\%$; 95% CI:-54.4 to 15.8). Similarly, no meaningful effects were observed for maximal sustained running speed ($\beta=-0.15$ km·h⁻¹; 95% CI:-2.12 to 1.82), total exercise time ($\beta=-0.42$ min; 95% CI:-2.51 to 1.67), or distance covered ($\beta=-0.21$ km; 95% CI:-0.79 to 0.36). In conclusion, four weeks of beta-alanine supplementation did not produce detectable improvements in physical performance or lactate markers in elite marathon runners living at altitude, with effect estimates indicating small and imprecise differences between groups.

Keywords: sports performance, endurance athletes, hypoxia, sports nutrition, exercise physiology

Introduction

Physical performance in elite marathon runners depends on a complex interaction of cardiovascular, metabolic, and neuromuscular adaptations, which are particularly relevant in contexts of training and residence at altitude. Chron-

ic exposure to hypoxic environments induces physiological modifications aimed at optimizing oxygen transport and utilization, which may confer competitive advantages in endurance events; however, it also imposes greater metabolic stress during high-intensity exercise, accelerating the accumulation

of metabolites associated with fatigue (Bonato et al., 2023; Stellingwerff et al., 2019).

In this context, ergogenic nutritional strategies have gained a central role as a complement to training, especially in endurance athletes who live or train at altitude. Among the supplements with the strongest scientific support is beta-alanine, a non-essential amino acid that acts as the rate-limiting precursor of intramuscular carnosine. Carnosine plays key roles as an intracellular proton (H^+) buffer, a modulator of oxidative stress, and a regulator of calcium sensitivity during excitation–contraction coupling. Together, these mechanisms may attenuate exercise-induced fatigue (Brisola & Zagatto, 2019; Hostrup & Bangsbo, 2016).

Available evidence indicates that beta-alanine supplementation consistently increases muscle carnosine content, which is particularly relevant during high-intensity, moderate-duration efforts where metabolic acidosis is a limiting factor for performance (Brisola & Zagatto, 2019). In endurance athletes, several controlled trials have reported improvements in variables related to time to exhaustion, maximal aerobic speed, and performance within the aerobic–anaerobic transition zone, following both acute and chronic supplementation protocols (Huerta-Ojeda et al., 2019; Marko et al., 2025; Ojeda et al., 2023).

However, findings are not uniform. A study conducted in long-distance runners did not observe significant improvements in prolonged performance tests, such as 5-km races, despite increases in molecular markers associated with beta-alanine transport (Franco et al., 2021). These discrepancies suggest that the ergogenic effects of beta-alanine may depend on the type of exercise test, effort duration, athlete physiological profile, and the environmental context in which performance is evaluated.

In hypoxic settings, the ergogenic potential of beta-alanine is of particular interest. Reduced partial pressure of oxygen increases reliance on glycolytic metabolism and the rate of H^+ accumulation during exercise, which could theoretically amplify the benefits of enhanced intramuscular buffering capacity. However, studies evaluating beta-alanine supplementation under hypoxic conditions have reported inconsistent results, particularly in continuous endurance tests, and most have been conducted in recreationally active individuals or under simulated hypoxia models (Patel et al., 2021; Saunders et al., 2014; Wang et al., 2019).

Despite the widespread use of beta-alanine in sport, there is a lack of research examining its effects in elite marathon runners chronically residing at altitude—a population characterized by specific physiological adaptations and metabolic demands. Moreover, few studies have simultaneously integrated physical performance indicators and blood lactate markers using incremental track running protocols, limiting understanding of the mechanisms underlying a potential ergogenic response in this context.

Most of the available evidence on beta-alanine supplementation has been generated in athletes training at sea level or in recreationally active and untrained populations, frequently under laboratory-based or simulated hypoxia conditions (Brisola & Zagatto, 2019; Franco et al., 2021; Marko et al., 2025; Wang et al., 2019). These models may not accurately represent the phys-

iological and metabolic profile of elite endurance athletes who chronically reside at high altitude, as long-term hypoxic exposure induces specific hematological, ventilatory, and metabolic adaptations that could modulate buffering requirements and lactate kinetics during exercise (Bonato et al., 2023; Stellingwerff et al., 2019). Consequently, the transferability of findings obtained in sea-level or non-elite cohorts to altitude-adapted marathon runners remains uncertain.

Therefore, the aim of the present study was to evaluate the effect of chronic beta-alanine supplementation on physical performance and blood lactate markers in elite marathon runners living at altitude, using a randomized, double-blind, placebo-controlled experimental design.

It was hypothesized that beta-alanine supplementation would improve performance indicators and lactate dynamics during a maximal incremental running test compared with placebo, since under hypoxic conditions the reduction in oxygen availability increases dependence on glycolytic metabolism and accelerates metabolic acidosis, which could theoretically amplify the ergogenic relevance of greater buffering capacity, even in athletes chronically adapted to altitude (Saunders et al., 2014; Stellingwerff et al., 2019).

Methods

Study design

A randomized, double-blind, placebo-controlled, parallel-group clinical trial was conducted, following methodological principles for experimental studies in humans and in accordance with the CONSORT guidelines for reporting randomized controlled trials. The study adopted a longitudinal pre–post intervention design with two assessment time points: before and after a four-week supplementation period (Schulz et al., 2010).

No formal sample size or power calculation was performed due to the exploratory nature of this study and the limited availability of elite marathon runners residing at high altitude. The sample size was based on comparable studies evaluating beta-alanine supplementation in endurance athletes (Franco et al., 2021; Huerta-Ojeda et al., 2019).

Participants and eligibility criteria

Participants were elite marathon runners specializing in half-marathon (21 km) and marathon (42 km) events, belonging to the National Marathon Runners Program led by the Peruvian Athletics Federation, based in the cities of Huancayo and Cusco, located at high altitude in Peru (3259–3399 m above sea level). Recruitment was conducted between January 10 and 28, 2022, on a voluntary basis and in coordination with the coaches of each training center, initially enrolling 26 athletes.

Eligibility assessment included male and female marathon runners aged 25–40 years, native residents of altitudes above 3000 m, who had not consumed beta-alanine supplements during the three months prior to the study, did not present active musculoskeletal injuries or gastrointestinal disorders, were not pregnant, and did not follow vegetarian or vegan diets.

After applying eligibility criteria, 12 marathon runners

met the requirements and were randomly assigned to the intervention groups in a 1:1 ratio. During follow-up, one participant withdrew for personal reasons unrelated to the intervention; therefore, the final analysis included 11 athletes: 5 in the

beta-alanine group (BA) and 6 in the placebo group (PLA). Participant flow through the study phases is presented in Figure 1, according to the CONSORT flow diagram.

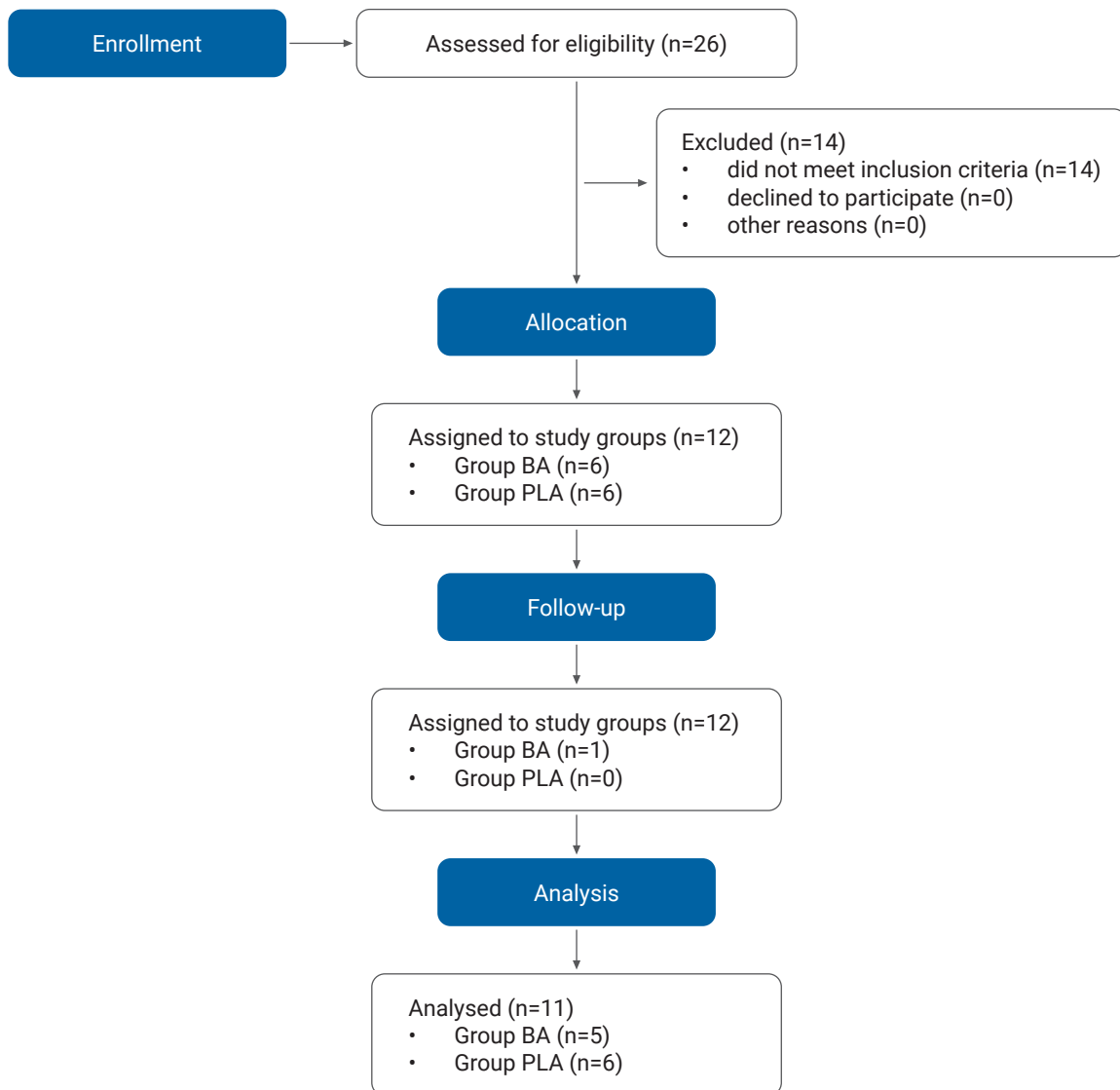


Figure 1. Flow of participants through each stage of the study

Randomization and blinding

Participants were assigned to the BA or PLA groups using simple randomization based on a computer-generated sequence. The study followed a double-blind design; participants, supplementation administrators, outcome assessors (for blood lactate, heart rate, and performance variables) and investigators responsible for data processing, and analysis were unaware of group allocation.

Supplements were encapsulated and presented in identical capsules in terms of appearance, taste, and packaging, and labeled with alphanumeric codes by an external investigator not involved in assessments or data analysis. The allocation code was disclosed only after completion of statistical analyses, ensuring maintenance of blinding throughout the intervention.

Procedures

After obtaining written informed consent, data collection was conducted at two time points (pre- and post-intervention). For both assessments, participants received standardized instructions: to consume their last meal at least 2 hours before testing, avoid strenuous exercise during the 3 hours prior, refrain from caffeine consumption for 24 hours, and maintain adequate hydration.

To standardize hydration status, participants were advised to consume approximately $30 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}$ of fluids during the three days preceding each evaluation, as well as $5\text{--}10 \text{ ml}\cdot\text{kg}^{-1}$ of water two hours before testing (Thomas et al., 2016; Trease et al., 2022).

Assessments were conducted between 10:00 and 13:00 h at the biomedical services of the High-Performance Centers

of the Peruvian Institute of Sport in Huancayo and Cusco. At each visit, hydration status was initially verified using the Armstrong urine color scale; in cases of hypohydration (scale 4–8), water intake was prescribed until an adequate hydration state was achieved (scale <4) before proceeding with measurements.

Anthropometry and dietary intake assessment

Body weight was measured barefoot and wearing light clothing using a digital scale (Omron Karada Scan HBF-701, Omron Healthcare Co., Ltd., Kyoto, Japan), with $\pm 1\%$ precision and automatic calibration. Height was measured using a stadiometer certified by the National Center for Food, Nutrition and Healthy Living (CENAN, Peru), with 0.1 cm precision. Measurements followed the recommendations of the International Society for the Advancement of Kinanthropometry (ISAK) (Esparza-Ros et al., 2019).

Body composition was assessed by bioelectrical impedance analysis using the same digital scale. Measurements followed a standardized protocol to minimize error sources, including relative fasting, bladder voiding prior to assessment, abstinence from intense physical exercise for at least 12 hours, and avoidance of caffeine or alcohol for 24 hours. Assessments were conducted in a controlled environment and at a similar time of day for each participant, following international recommendations for bioelectrical impedance use (Kyle et al., 2004).

Dietary intake was assessed using a 24-hour dietary recall applied the day prior to each assessment (pre- and post-intervention), employing the multiple-pass method, which consists of a structured, multi-stage interview to facilitate comprehensive recall of all foods and beverages consumed. This method has demonstrated higher validity and reproducibility in adult dietary assessment (Conway et al., 2004). Portion size estimation was supported by visual aids based on auxiliary tables for dietary formulation and evaluation (Domínguez et al., 2016). Intake values were expressed as kilocalories per day and grams per day of macronutrients, and relative intake per body weight ($\text{kcal}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}$ and $\text{g}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}$) was used for analysis.

Supplementation protocol

Participants assigned to the BA group received a daily dose of 6 g of beta-alanine (Nutricost®, USA), divided into two 3 g doses to minimize paresthesia. The PLA group received 6 g·day⁻¹ of maltodextrin (Nutricost®, USA) under the same administration scheme. Supplementation was maintained for four consecutive weeks, with periodic monitoring to ensure protocol adherence.

Supplement adherence was monitored by weekly follow-up calls and pill counts at the end of the intervention. Participants were instructed to report any missed doses, and adherence was defined as consuming $\geq 90\%$ of the assigned capsules.

Maximal incremental running test

After a standardized 15-minute warm-up consisting of dynamic running exercises, participants performed a maximal incremental running test on a 400 m outdoor track. Male participants started at an approximate pace of 1:30 min per lap, while females started at 1:40 min per lap, with progressive

speed increases each lap until voluntary exhaustion. This protocol was designed to induce controlled, progressive increases in external load in a field setting, allowing assessment of maximal performance under conditions that validly replicate the physiological and mechanical demands of endurance running at altitude (Midgley et al., 2007).

Physical performance assessment

Capillary blood lactate samples were obtained using a portable analyzer (Lactate Pro 2, Arkay Inc., Kyoto, Japan) at three standardized time points: at rest, immediately after the final lap (post), and after 3 minutes of active recovery. Samples were collected from the ear lobe to ensure consistency across participants. This allowed determination of maximal lactate concentration, post-rest lactate difference, and lactate clearance rate, calculated as the percentage reduction between maximal lactate and the value at 3 minutes post-test.

Heart rate was recorded at the end of each lap using a Polar RS800 monitor (Polar Electro Oy, Kempele, Finland), enabling estimation of mean heart rate during the test and maximal heart rate achieved at the end of the final lap. Rating of perceived exertion (RPE) was assessed at test completion using the 20-point Borg scale.

Pace (mm:ss), mean speed, and lap time were recorded to calculate maximal sustained speed, total exercise time, and total distance covered during the test.

Ethical considerations

The study was approved by the Ethics Committee of Universidad Norbert Wiener (approval code: No. 052-2021) and conducted in accordance with the ethical principles of the Declaration of Helsinki (World Medical Association, 2013), as well as the principles of scientific integrity outlined in the Singapore Statement on Research Integrity (World Conference on Research Integrity, 2010). All marathon runners provided written informed consent, and data confidentiality was ensured in compliance with Peruvian Personal Data Protection Law No. 29733.

Statistical analysis

Descriptive statistics were used to characterize baseline sample characteristics, reporting means and standard deviations (SD) for continuous variables and absolute and relative frequencies for categorical variables. Normality of continuous variables was assessed using the Shapiro–Wilk test. Baseline comparability between experimental and placebo groups was evaluated using independent-samples Student's t-tests for numerical variables.

Pre- and post-intervention changes were analyzed using linear mixed-effects regression models, accounting for the longitudinal nature of the data. These models included a random intercept at the participant level to capture within-subject correlation of repeated measurements. Study group (BA vs. PLA), time (post vs. pre), and the group \times time interaction were modeled as fixed effects, with the interaction term serving as the primary parameter to estimate the effect of beta-alanine supplementation.

Mixed-effects models were preferred over paired analyses or ANCOVA due to their greater flexibility in handling individual variability. Model assumptions, including normality of residuals and homoscedasticity, were checked prior to analysis. These models can provide unbiased estimates in the presence of missing data under the missing-at-random assumption, robust standard errors were used to ensure valid statistical inference in case of deviations from assumptions.

To illustrate changes in maximal sustained speed during the maximal incremental running test on the 400 m track over time, a line graph representing group means and 95% confidence intervals was constructed. Statistical analyses were primarily conducted using SPSS software version 22.0 (IBM Corp., Armonk, NY, USA), and a p -value <0.05 was considered statistically significant.

Results

The baseline characteristics of the marathon runners included in the analysis are presented in Table 1. A total of 11 athletes completed the study, with 6 allocated to the placebo group (PLA) and 5 to the beta-alanine group (BA). Sex distribution was comparable between groups, with a similar proportion of male and female participants. Mean age was 28.5 ± 1.8 years in the PLA group and 30.0 ± 2.9 years in the BA group ($p > 0.05$). No statistically significant differences were observed between groups in any of the anthropometric or body composition variables assessed at baseline ($p > 0.05$).

These findings indicate adequate baseline comparability between the study groups prior to the intervention.

Table 1. Baseline characteristics of marathon runners by study group

Variable		PLA (n=6)	BA (n=5)	p-value
Sex		n (%)		
	Male	3	3	
	Female	3	2	
		Mean \pm SD		
Age	years	28.5 ± 1.8	30.0 ± 2.9	0.67
Body weight	kg	54.4 ± 2.4	56.9 ± 5.2	0.67
Height	cm	160.6 ± 2.1	164.6 ± 4.2	0.42
BMI	kg/m ²	21.1 ± 0.5	20.8 ± 1.0	0.82
Body fat	%	20.5 ± 2.7	25.2 ± 2.1	0.21
Muscle mass	%	30.5 ± 2.2	30.1 ± 1.3	0.88

Note. PLA = placebo group; BA = beta-alanine group; BMI = body mass index; p -value obtained using Student's t -test for independent samples.

Energy and macronutrient intake before and after the intervention is presented in Table 2. At baseline, no statistically significant differences were observed between the placebo (PLA) and beta-alanine (BA) groups in total energy intake or in body weight-adjusted protein, carbohydrate, or fat intake ($p > 0.05$).

Throughout the intervention period, both groups main-

tained comparable energy and macronutrient intakes, with no relevant changes observed between the pre- and post-intervention assessments. These findings suggest that dietary intake was similar between groups and remained relatively stable over the course of the study, thereby minimizing its potential confounding effect on the performance-related outcomes evaluated.

Table 2. Energy and macronutrient intake before and after the intervention

Variable	PLA		BA		p-value
	Pre	Post	Pre	Post	
Energy (kcal·kg ⁻¹ ·día ⁻¹)	42.9 ± 14.1	48.0 ± 13.2	44.9 ± 5.6	45.7 ± 8.4	0.77
Protein (g·kg ⁻¹ ·día ⁻¹)	1.8 ± 0.7	2.0 ± 0.6	1.9 ± 0.6	2.0 ± 0.6	0.74
Carbohydrates (g·kg ⁻¹ ·día ⁻¹)	5.4 ± 1.3	6.4 ± 1.9	6.0 ± 0.8	5.9 ± 1.5	0.37
Fat (g·kg ⁻¹ ·día ⁻¹)	1.7 ± 0.9	1.7 ± 0.8	1.4 ± 0.4	1.6 ± 0.6	0.57

Note. PLA = placebo group; BA = beta-alanine group; Pre = pre-intervention; Post = post-intervention. p -value obtained using Student's t -test for independent samples (PLA-pre vs. BA-pre)

Changes in blood lactate markers before and after the intervention are presented in Table 3. No statistically significant differences were observed between the placebo (PLA) and beta-alanine (BA) groups in maximal lactate concentration achieved during the incremental test, according to the group \times time interaction effect ($\beta = -1.29 \text{ mmol}\cdot\text{L}^{-1}$; 95% CI: -4.81 to 2.23 ; $p = 0.42$).

Similarly, no significant effects of supplementation were found for post-rest lactate difference ($\beta = -1.77 \text{ mmol}\cdot\text{L}^{-1}$; 95% CI: -5.67 to 2.12 ; $p = 0.33$) or for lactate clearance percentage ($\beta = -19.27\%$; 95% CI: -54.4 to 15.8 ; $p = 0.24$). Overall, these results indicate that beta-alanine supplementation did not induce detectable changes in blood lactate responses during or after maximal exercise testing compared with placebo.

Table 3. Effect of beta-alanine supplementation on blood lactate markers during a maximal incremental test

Variable	PLA		BA		β (G \times T)	95%IC	p-value
	Pre	Post	Pre	Post			
Lactate _{max} (mmol·L ⁻¹)	6.5 \pm 1.7	7.1 \pm 2.0	7.9 \pm 3.1	7.1 \pm 2.8	-1.29	-4.81-2.23	0.42
Δ Lactate _{post-rest} (mmol·L ⁻¹)	4.7 \pm 1.9	5.6 \pm 2.1	6.2 \pm 2.9	5.3 \pm 3.4	-1.77	-5.67-2.12	0.33
Lactate clearance (%)	12.9 \pm 23.4	6.5 \pm 10.3	8.5 \pm 11.2	-17.2 \pm 32.5	-19.27	-54.4-15.8	0.24

Note. PLA = placebo group; BA = beta-alanine group; max = maximum; Pre = pre-intervention; Post = post-intervention. The β (G \times T) coefficient represents the group \times time interaction effect (BA vs. PLA; post vs. pre). 95% CI: 95% confidence interval.

The effect of beta-alanine supplementation on physical performance variables is presented in Table 4. No statistically significant differences were observed between the placebo (PLA) and beta-alanine (BA) groups in maximal sustained running speed during the maximal incremental test, according to the group \times time interaction effect ($\beta = -0.15 \text{ km}\cdot\text{h}^{-1}$; 95% CI: -2.12 to 1.82 ; $p = 0.86$). Consistently, maximal sustained speed was similar between groups at both pre- and post-intervention assessments, with no significant changes over time (Figure 2).

($\beta = -0.21 \text{ km}$; 95% CI: -0.79 to 0.36 ; $p = 0.42$). No significant differences were observed in cardiovascular responses, including maximal heart rate achieved ($\beta = -3.23 \text{ bpm}$; 95% CI: -16.6 to 10.2 ; $p = 0.59$) and mean heart rate during the test ($\beta = 2.59 \text{ bpm}$; 95% CI: -10.0 to 15.2 ; $p = 0.65$).

Likewise, no significant effects of the intervention were detected on total exercise time ($\beta = -0.42 \text{ min}$; 95% CI: -2.51 to 1.67 ; $p = 0.66$) or on total distance covered during the test

Furthermore, maximal rating of perceived exertion (RPE) was comparable between groups and did not show significant changes following the intervention ($\beta = 0.20$; 95% CI: -1.43 to 1.83 ; $p = 0.78$). Overall, these results indicate that beta-alanine supplementation did not produce detectable improvements in physical performance or in the physiological responses assessed during the maximal incremental test compared with placebo.

Table 4. Effect of beta-alanine supplementation on physical performance during a maximal incremental test

Variable	PLA		BA		β (G \times T)	95%IC	p-value
	Pre	Post	Pre	Post			
Sustained speed _{max} (km·h ⁻¹)	19.1 \pm 2.0	19.4 \pm 1.0	19.5 \pm 2.9	19.6 \pm 2.7	-0.15	-2.12-1.82	0.86
Total exercise time (min)	7.3 \pm 1.3	6.2 \pm 1.1	7.4 \pm 1.2	5.9 \pm 0.8	-0.42	-2.51-1.67	0.66
Total distance (km)	2.1 \pm 0.4	1.8 \pm 0.3	2.2 \pm 0.5	1.7 \pm 0.2	-0.21	-0.79-0.36	0.42
HR _{max} (lpm)	165.0 \pm 9.1	165.8 \pm 6.9	167.0 \pm 11.2	164.6 \pm 7.2	-3.23	-16.6-10.2	0.59
HR _{mean} (lpm)	152.5 \pm 12.1	154.0 \pm 7.1	151.9 \pm 5.9	156.0 \pm 10.7	2.59	-10.0-15.2	0.65
RPE _{max}	17.8 \pm 1.2	17.8 \pm 0.8	17.6 \pm 0.5	17.8 \pm 0.8	0.20	-1.43-1.83	0.78

Note. PLA = placebo group; BA = beta-alanine group; Pre = pre-intervention; Post = post-intervention; HR = heart rate; RPE = rating of perceived exertion; max = maximum; The β (G \times T) coefficient represents the group \times time interaction effect (BA vs. PLA; post vs. pre). 95% CI: 95% confidence Interval.

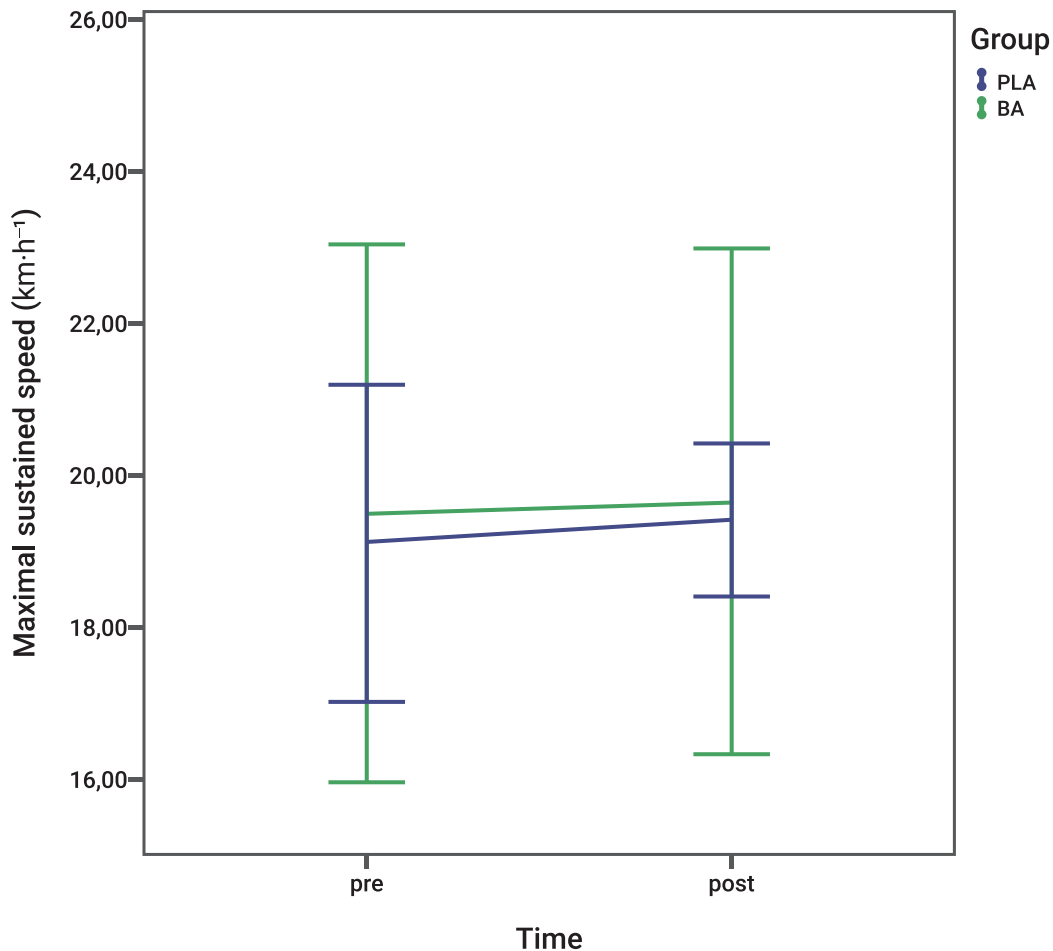


Figure 2. Maximal sustained running speed before and after the intervention in marathon runners assigned to placebo and beta-alanine

Note. Data represent group means \pm 95% confidence intervals. The x-axis shows time points (pre- and post-intervention), and the y-axis shows maximal sustained speed in $\text{km}\cdot\text{h}^{-1}$. BA = beta-alanine group; PLA = placebo group.

Discussion

The present study evaluated the effect of four weeks of beta-alanine supplementation on physical performance and blood lactate markers in highly trained marathon runners residing at altitude, finding no significant differences compared with placebo. These null findings may be influenced by the chronic adaptations to altitude, which include enhanced oxygen delivery, altered acid-base balance, and improved metabolic efficiency, potentially overriding the additional buffering benefits provided by beta-alanine (Bonato et al., 2023; Stellingwerff et al., 2019).

These results partially contrast with studies reporting ergogenic benefits of beta-alanine in endurance athletes, particularly when acute supplementation protocols are employed or when exercise tests are conducted at intensity domains near the aerobic-anaerobic transition (Barahona-Fuentes et al., 2023; Ducker et al., 2013; Huerta-Ojeda et al., 2019; Ojeda et al., 2023). Individual variability, including the presence of non-responders, may also contribute to the heterogeneous responses observed in previous research (Hostrup & Bangsbo, 2016).

Conversely, our results are consistent with investigations

that have not demonstrated clear benefits of beta-alanine supplementation in prolonged endurance performance. Franco et al. (2021) reported that four weeks of beta-alanine supplementation ($4.8 \text{ g}\cdot\text{day}^{-1}$) did not improve performance in a 5-km time trial in endurance runners, despite observing increased expression of the PAT1 transporter. Similarly, Patel et al. (2021) found no improvements in high-intensity exercise capacity under either normoxic or hypoxic conditions following 28 days of beta-alanine supplementation.

These findings suggest that the ergogenic effects of beta-alanine may be more pronounced in short, high-intensity efforts (1–4 minutes) rather than in long-duration endurance exercise, particularly in athletes already adapted to chronic hypoxia (Barahona-Fuentes et al., 2023; Brisola & Zagatto, 2019; Ducker et al., 2013; Huerta-Ojeda et al., 2019; Ojeda et al., 2023).

Beta-alanine, blood lactate, and metabolic buffering under chronic hypoxia

From a physiological perspective, beta-alanine increases muscle carnosine content, a dipeptide with buffering capacity against hydrogen ion accumulation during intense exercise

(Hostrup & Bangsbo, 2016). However, evidence suggests that this mechanism is more relevant during predominantly glycolytic exercise.

In the present study, no significant changes were observed in maximal lactate concentration, post-rest lactate difference, or lactate clearance percentage, which is consistent with the findings of Ducker et al. (2013). Despite reporting improved 800-m performance following beta-alanine supplementation, these authors did not observe significant changes in blood lactate concentration or post-exercise pH.

Moreover, in runners chronically adapted to altitude, prolonged exposure to hypoxia induces metabolic and ventilatory adaptations that may attenuate the additional impact of buffering supplements. In this context, Stellingwerff et al. (2019) emphasize that performance optimization at altitude relies more heavily on energy availability, iron status, and appropriate nutritional periodization than on the isolated use of ergogenic supplements.

Strengths and limitations

Among the main strengths of this study are its randomized, double-blind, placebo-controlled design, as well as the assessment conducted under ecologically valid field conditions in athletes residing at high altitude, a population that remains underrepresented in the literature.

Nevertheless, several limitations should be acknowledged. First, the small sample size limits the statistical power to detect small effect sizes. Second, muscle carnosine content was not directly measured, preventing confirmation of the biological effectiveness of the supplementation protocol. Finally, short supplementation duration that may be insufficient to induce measurable changes in highly trained athletes.

Practical implications

From an applied perspective, the results of this study suggest that chronic beta-alanine supplementation (6 g·day⁻¹ for four weeks) does not provide additional benefits in physical performance or blood lactate markers in highly trained marathon runners residing at altitude. In athletes who are highly trained and chronically adapted to hypoxia, the margin for improvement attributable to supplementation appears to be limited.

Therefore, the use of beta-alanine may be more relevant in middle-distance endurance disciplines or in events involving pronounced aerobic-anaerobic transitions, as evidenced in studies involving middle-distance runners (Ducker et al., 2013; Huerta-Ojeda et al., 2019; Ojeda et al., 2023), rather than in marathon or half-marathon events.

Future research directions

Future studies should explore individualized supplementation protocols, consider combinations with other buffering agents (e.g., sodium bicarbonate), and assess effects using competition-specific performance tests. Additionally, investigating interindividual variability and the role of muscle fiber type in altitude-adapted athletes appears warranted, as suggested by Hostrup and Bangsbo (2016).

Conclusions

In the evaluated sample of highly trained marathon runners residing at altitude, beta-alanine supplementation at a dose of 6 g/day for four weeks did not produce significant improvements in physical performance assessed through a maximal incremental track test, nor in associated physiological responses, including maximal sustained speed, total exercise time, distance covered, heart rate, and perceived exertion. Furthermore, the intervention did not induce meaningful changes in blood lactate markers, such as maximal lactate concentration, lactate clearance, or post-rest variation, suggesting that beta-alanine did not substantially modify metabolic balance during maximal exercise.

For coaches and athletes, this indicates that beta-alanine may not be useful for long-distance events at altitude, though it could be relevant for shorter, high-intensity endurance activities. Importantly, these results apply specifically to highly trained marathon runners and should not be generalized to all endurance athletes.

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Conflict of Interest

The authors declare no conflicts of interest.

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Suboptimal Hydration in Collegian Folk Dancers - A Two-Microcycle Assessment of Fluid Intake and Urine Specific Gravity: An Exploratory Study

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Abstract

Proper hydration is essential for performance and health in physically demanding activities such as folk dancing. This exploratory study aimed to evaluate the hydration practices and hydration levels of collegiate folklore ensemble dancers by measuring urine specific gravity (USG) and monitoring fluid intake. A total of 18 dancers (7 males aged 17.54 ± 1.77 years, and 11 females aged 17.22 ± 1.87 years) participated in this study. Fluid intake was self-reported daily, and USG was measured from morning urine samples on training days. In analyzing men's USG values, no significant differences were found between the first and second microcycle (1.018 vs. 1.019 g.ml⁻¹); however, a medium practical effect was observed ($p=0.469$; $r=0.45$). Two males were hypohydrated during the whole study, and five were mildly hypohydrated. In contrast, the analysis for women (1.014 v. 1.012 g.ml⁻¹) revealed significant differences in USG across microcycles, indicating a large practical effect ($p=0.001$; $r=0.87$). One female was hypohydrated during the whole period, and ten were constantly mildly hypohydrated. Differences in males' fluid intake between microcycles (2.08 vs. 1.84 l/day) were insignificant, but with a large practical effect ($p=0.100$; $r=0.76$). Females showed no significant difference (1.92 vs. 1.81 l/day), with no practical effect ($p=0.700$; $r=0.08$). When analyzing intrasexual differences, we found significant differences ($U=245.5$; $p=0.004$) in USG values, which were higher in men, indicating a higher degree of hypohydration. Differences in fluid intake between the sexes were not observed ($U=160.5$; $p=0.846$), and average consumption was below recommended guidelines. These findings underscore the need for targeted hydration education to mitigate performance and health risks in our subjects. Promoting awareness and implementing tailored hydration strategies may enhance performance, cognitive function, and injury prevention in folklore dancers.

Keywords: dancing, physical performance, microcycle, fluid intake, USG

Introduction

Dance, as a form of human movement and cultural expression, occupies a unique position at the intersection of art, physical exertion, and ritual. Among its many forms, traditional folk dance is especially rich in ethnographic significance, serving as a medium for transmitting intangible cultural heritage across generations (Zhou & Chen, 2024). Folk dancers are not merely artists but highly conditioned performers who must harmonize aesthetic precision with substantial physical output (Oreb et al., 2011). From a physiological standpoint, traditional folk dance represents a hybrid load characterized by alternating aerobic and anaerobic energy demands. The execution of technically demanding movement patterns, often in elaborate and thermally insulating costumes, increases both metabolic rate and core body temperature, intensifying the need for effective thermoregulation and hydration (Örer & Doğu, 2017).

Dehydration, particularly hypohydration induced by insufficient fluid intake or excessive fluid loss, has been linked to a decrement in neuromuscular function, thermoregulatory capacity, cardiovascular efficiency, and cognitive performance (Armstrong, 2007). These consequences are especially relevant in dance settings, where optimal motor coordination, rhythm perception, and reaction timing are crucial for performance and injury prevention.

Moreover, the thermoregulatory burden experienced during dance rehearsals and performances, especially in warm environments or under stage lighting, can significantly accelerate fluid loss through perspiration. This burden is exacerbated by traditional costumes that limit heat dissipation, increasing susceptibility to dehydration (Rivera-Brown & De Félix-Dávila, 2012). Even mild hypohydration, defined as a loss of body water under 2% of body mass, has been shown to impair endurance performance and cognitive function (Armstrong, 2007; Jéquier & Constant, 2010). Despite these risks, research consistently reports a lack of awareness among dancers regarding hydration strategies and fluid requirements (Schmidt et al., 2024).

USG is a widely accepted, non-invasive biomarker of hydration status (Chapelle et al., 2017). In field conditions such as dance training, USG offers a feasible alternative to monitor hydration longitudinally.

However, the majority of studies examining hydration behaviour and status have focused on athletes in mainstream sports, with relatively little attention devoted to dance populations, particularly traditional or folk dancers, whose training conditions and cultural settings differ markedly from those of other physically active groups (Pettersson & Berg, 2014; Volpe et al., 2009). As a result, there exists a critical gap in our understanding of hydration patterns in this unique cohort. This gap is particularly relevant in younger, pre-professional dancers exposed to cumulative training loads under real-world conditions.

The primary aim of this exploratory study was to assess the hydration status and daily fluid intake in male and female collegiate folk dancers over two consecutive training microcycles. We hypothesized that dancers would exhibit signs of hypohydration, reflected by elevated USG values and fluid

intake below recommended guidelines, and that differences would be present between sexes and across microcycles.

Methods

Study design

In our study, we conducted a repeated-measures observational study to compare fluid intake and USG among dancers across two consecutive training microcycles. A training microcycle was defined as a one-week (7-day) period reflecting the ensemble's standard training routine. Additionally, we compared these findings with established reference values. In the subsequent phase, we examined the presence of intersex differences. Fluid intake was monitored on a regular daily basis, both on training and non-training days. Training frequency, duration, and structure were consistent across both microcycles, and no intentional manipulation of training intensity or load was implemented. The dancers recorded the amount of fluid intake in litres on prepared recording sheets. USG was collected each morning upon waking on training days, approximately 10 hours before the scheduled start of training sessions. USG measures the relative density of urine compared to distilled water. This parameter is used to assess an individual's hydration status. Normally hydrated individuals have diluted urine, while those who are hypohydrated have more concentrated urine (Warren et al., 2018).

Participants

The young dancers from the College Folklore Ensemble "Mladost" participated voluntarily in our study, with written consent obtained from their legal guardians. The male participants ($n=7$) had an average age of 17.54 ± 1.77 years, weighed 64.14 ± 5.73 kg, and had an average height of 180.43 ± 7.93 cm. The female participants ($n=11$) were 17.22 ± 1.87 years old, weighed 58.00 ± 4.31 kg, and had an average height of 167.00 ± 6.02 cm. The participants were experienced dancers, with an average training experience of 10.5 ± 2.75 years. The group practiced twice a week and took part in various dance performances and folklore festivals throughout the year. All participants in the research were healthy and had no injuries to their musculoskeletal systems. Legal representatives signed informed consent forms to confirm voluntary participation in the study. The research was approved by the local ethics committee under number 1/2024. The subjects were instructed not to consume any caffeine or alcohol during the experiment.

Measurements

Before the start of the study, all participants were provided with non-sterile tubes to use for sampling and recording sheets for fluid intake. Urine collection was conducted by all participants in the morning after waking up, while fasting, on training days, for a total of 4 times. To strictly adhere to the methodological procedures, we relied on proven methodologies of previous research. Wardenaar et al. (2021) state that an optimum temperature of $20\text{ }^{\circ}\text{C}$ should be ensured for urine density measurements; however, temperature differences up to $37\text{ }^{\circ}\text{C}$ do not affect the measurement results. Our samples

were stored in a refrigerated box and cooled to 7 °C (without a water bath) after collection. The samples were analyzed after a period of 24 hours. We waited until the samples reached room temperature. Due to the resulting sedimentation of urine, all tubes were thoroughly mixed before evaluation. An ATAGO - PAL10S (Made in Japan) pocket refractometer was used to analyse the samples, which can evaluate the USG of the applied sample in g/mL-1 in a few seconds for the examiner. A USG value of less than 1.010 g.ml-1 indicates a euhydrated state, while values between 1.010 and 1.019 g.ml-1 illustrate minimal hypohydration. USG values higher than 1.020 g.ml-1 may indicate hypohydration, and values higher than 1.030 g.ml-1 indicate a state of severe hypohydration (Chapelle et al., 2017). Before taking the initial measurement, we calibrated the instrument according to the manufacturer's instructions by applying distilled water until it registered 1.000 g/ml-1. The refractometer featured an NFC connection, allowing for easy transmission of the measured data to a computer. Fluid intake was monitored daily (on training and non-training days) over two consecutive microcycles. Bottles labelled with the amount of water intake were provided to the participants. The type and amount of fluid ingested were solely the choice of the dancers and were based on their everyday habits. No hydration education, counseling, or specific drinking instructions were provided before or during the study to preserve habitual hydration behavior. Self-reported fluid intake was chosen for its practicality and minimal disruption to usual behavior in a real-world training setting. Objective verification methods such as bottle weighing or pre-post body mass assessment were not employed to avoid influencing participants' natural drinking behavior. Fluid types varied and included water, mineral water, and sugary beverages, which may affect hydration status beyond total volume. This variability is recognized as a potential source of bias.

Statistical analysis

We evaluated the normality of the data distribution using the Shapiro-Wilk test, assessing the measured data separately for men and women. We used Wilcoxon's signed-rank test to compare the first and second microcycles. Additionally, we applied Wilcoxon's signed-rank test to evaluate the measured USG values against the reference values. The Mann-Whitney U-test was conducted to analyze differences between the sexes. A p-value of ≤ 0.05 was considered statistically significant. Cohen's r was used to determine the effect sizes. All data analyses were performed using IBM SPSS software (Version 23 for Windows; IBM, Armonk, NY, USA). Data are presented as median values with interquartile range.

Results

In the first and second microcycles, we recorded median USG values of 1.018 (IQR=0.010) g.ml-1 and 1.019 (IQR=0.004) g.ml-1 in male dancers (Table 1). This represents a +0.10% change in USG across microcycles. The differences were not found to be significant ($p=0.469$), with a medium effect size ($r=0.45$) (Figure 1). Fluid intake in male participants (Figure 2) was 2.08 l/day in the first and even lower in the second microcycle, with 1.84 l/day. This indicates a decrease of 11.5% in daily fluid intake between microcycles. Despite the lack of statistical significance, the large effect size suggests a practically meaningful reduction in fluid intake. In females (Figure 3), the USG values were higher in the first (1.014; IQR=0.005 g.ml-1) compared to the second microcycle (1.012; IQR=0.006 g.ml-1), with significant differences and a large practical effect ($p=0.001$; $r=0.87$). This indicates a positive change of 0.20% in USG values across microcycles. In the first microcycle, the female subject had a daily fluid intake (Figure 4) of 1.92 liters, which decreased to 1.81 liters in the second microcycle. There were no significant differences noted between the two microcycles, and the effect size was negligible ($p=0.700$; $r=0.08$). This reflects a 5.7% reduction in daily fluid intake.

In comparing the measured values of USG with the reference value of 1.010 g.ml-1, we observed mild hypohydration in both sexes. For males, the USG was 1.018 g.ml-1 in the first microcycle ($p=0.016$) and 1.019 g.ml-1 in the second microcycle ($p=0.016$). Based on USG thresholds, 5 of 7 male dancers met the criteria for mild hypohydration ($USG \geq 1.010$ g.ml⁻¹) in both microcycles; two were hypohydrated, while none reached values indicative of severe hypohydration. For females, the USG readings were 1.014 g/ml-1 in the first microcycle ($p=0.001$) and 1.012 g.ml-1 in the second microcycle ($p=0.001$). Among female dancers, 10 of 11 met the criteria for mild hypohydration in both microcycles; one was hypohydrated, and no cases of severe hypohydration were observed. The consistent elevation of USG values above the normative threshold of 1.010 g.ml⁻¹ highlights a persistent pattern of suboptimal hydration.

When comparing both sexes (Figure 5), significant differences were found in USG values ($U=245.5$; $p=0.004$), which were higher in male men, indicating a greater degree of hypohydration compared to women. This finding indicates that male dancers probably entered training sessions in a less favorable hydration state. Differences in fluid intake (Figure 6) between the sexes were not confirmed ($U=160.5$; $p=0.846$). Daily fluid intake in both sexes remained below the European Food Safety Authority (EFSA) and the Institute of Medicine recommendations throughout both microcycles.

Table 1. Median values and interquartile range of USG and Fluid intake for male and female dancers in the 1st and 2nd microcycle

	USG g.ml ⁻¹				Fluid Intake (l)			
	1 st microcycle	IQR	2 nd microcycle	IQR	1 st microcycle	IQR	2 nd microcycle	IQR
Male	1.018	0.010	1.019	0.004	2.08	0.670	1.84	0.900
Female	1.014	0.005	1.012	0.006	1.92	0.600	1.81	0.210

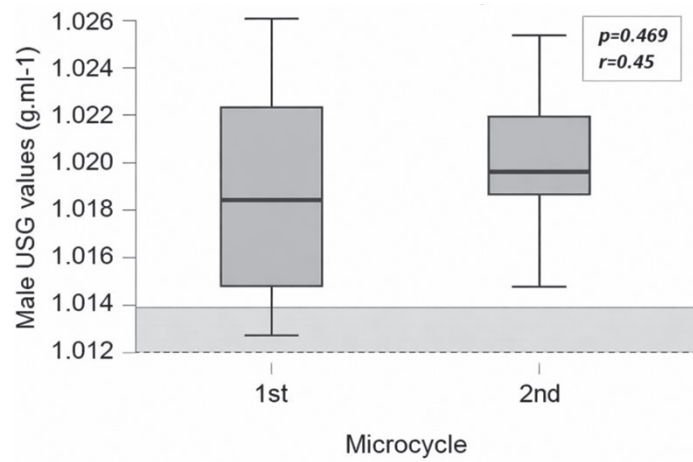


Figure 1. USG values in male dancers across two training microcycles
 Note. *p* – statistical significance, *r* – effect size. The shaded area represents the normative threshold for euhydration ($USG \leq 1.010 \text{ g}\cdot\text{ml}^{-1}$)

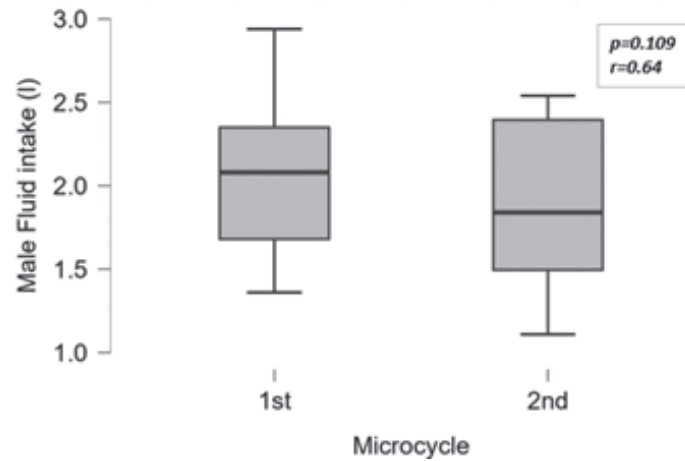


Figure 2. Daily fluid intake in male dancers across two training microcycles
 Note. *p* – statistical significance, *r* – effect size

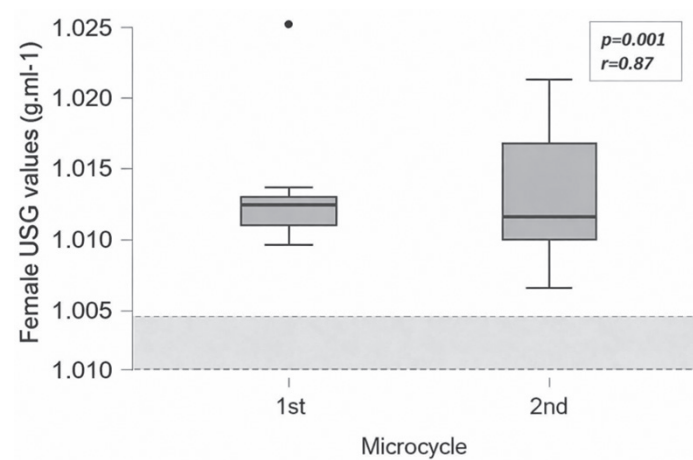


Figure 3. USG values in female dancers across two training microcycles
 Note. *p* – statistical significance, *r* – effect size. The shaded area represents the normative threshold for euhydration ($USG \leq 1.010 \text{ g}\cdot\text{ml}^{-1}$)

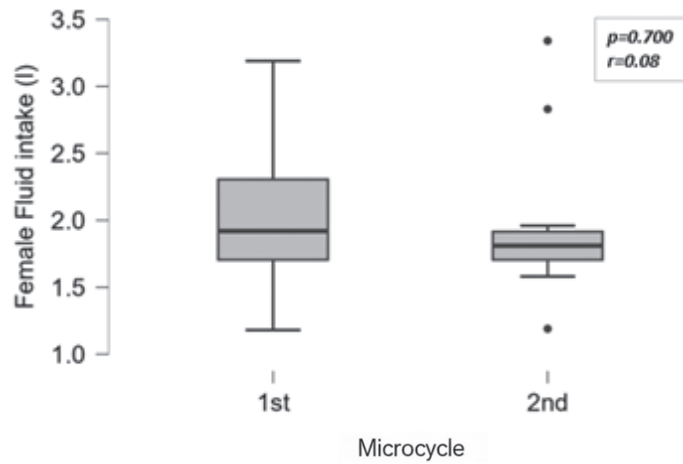


Figure 4. Daily fluid intake in dancers across two training microcycles
 Note. p – statistical significance, r – effect size

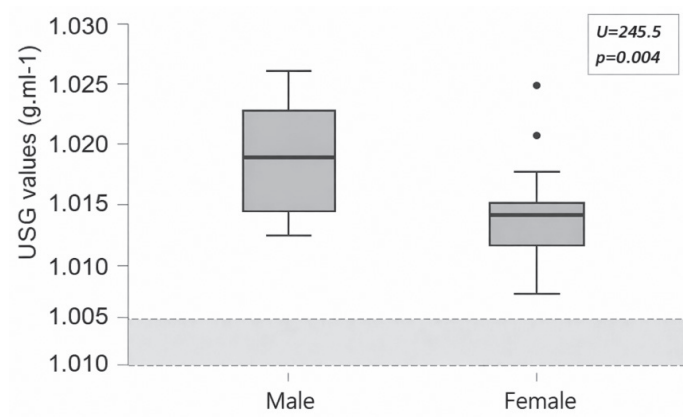


Figure 5. Comparison of USG values between male and female dancers
 Note. U – Mann-Whitney U-test, p – statistical significance. The shaded area represents the normative euhydration threshold ($USG \leq 1.010 \text{ g}\cdot\text{ml}^{-1}$)

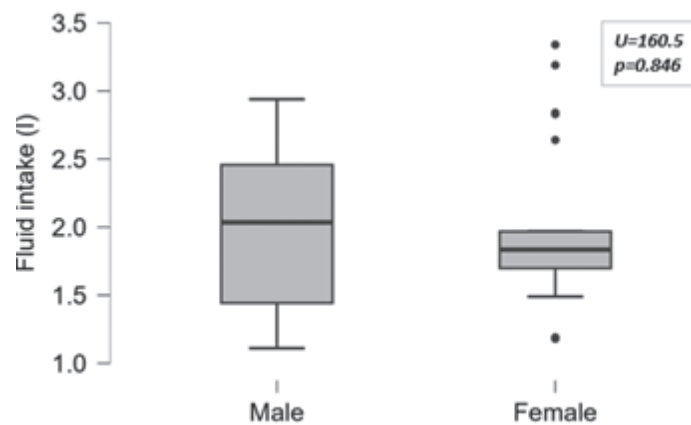


Figure 6. Comparison of daily fluid intake between male and female dancers
 Note. U – Mann-Whitney U-test, p – statistical significance

Discussion

Hydration changes across training microcycles

The present study examined hydration status and fluid intake across two consecutive training microcycles in collegiate folk dancers.

Male USG values did not show significant changes over two consecutive training microcycles. However, fluid intake decreased in the second microcycle by an average of 0.24 liters per day. While this difference was not statistically significant, the observed large effect size indicates a practically relevant decline in fluid intake. In our study, the median USG values for males were on the borderline between mild hypohydration and hypohydration. This indicates an increased risk that dancers may not begin their training fully hydrated. Insufficient hydration can negatively impact their cardiovascular and thermoregulatory responses, lead to heightened feelings of exertion, and hinder recovery, especially when training load is cumulative (Phillips et al., 2014). In terms of performance, even a slight change (as little as 1–2% of body weight, often accompanied by an increase in USG) can impair thermoregulation, perceived exertion, and cognitive function. This impairment can compromise training or competition, especially during repeated microcycles (Armstrong et al., 2025). Although the decrease in fluid intake of 0.24 liters per day was not statistically significant, it may indicate a practically relevant shift towards hypohydration, given the borderline values of USG. This highlights the importance of monitoring and educating folk dancers about hydration (Wardenaar et al., 2021).

In female dancers, a significant decrease in USG values was observed between microcycles, indicating an improvement in hydration status. Despite that, their USG values remained below the optimal hydration level, which, according to the classification by Chapelle et al. (2017, 2020), indicates mild hypohydration. Fluid intake for the women was nearly unchanged across both microcycles, with a slight decrease of only -0.11 liters per day during the second microcycle. The improvement in USG and consistent daily fluid intake indicate that factors beyond total fluid volume may have influenced the enhanced hydration status (Guelinckx et al., 2016). Approximately 20–30% of daily water intake comes from food, and with a higher proportion of foods with high water content (soups, fruits, vegetables), hydration can improve even without changing the declared drinking regime. In contrast, male dancers demonstrated stable USG values across microcycles, accompanied by a reduction in daily fluid intake.

Overall, our results suggest a tendency toward sub-optimal hydration, with USG values consistently above the recommended threshold of 1.010 g.ml⁻¹, yet still within the range classified as minimal hypohydration (Chapelle et al., 2017; Gibson et al., 2012). These findings are consistent with earlier reports in athletes and dancers, which show that mild hypohydration is common and often overlooked in training environments (Gibson et al., 2012; Tanabe et al., 2021).

Sex-specific differences in hydration status

Male dancers consistently exhibited higher USG compared to females, indicating a greater degree of hypohydra-

tion. While statistical significance supports this difference, its practical relevance is underscored by the consistent elevation of USG above normative thresholds across both microcycles. Males entered training sessions probably in a worse state of hydration than females. Several studies also report that male athletes tend to have higher USG levels and a greater proportion of hypohydrated individuals before training compared to their female counterparts (Volpe et al., 2009). There were no significant differences in fluid intake between the sexes in our study. Both groups demonstrated a reduction in fluid consumption across microcycles, which may indicate a gradual neglect of hydration habits during the training process. Self-reported values should be interpreted with caution, but this downward trend is noteworthy, as inadequate fluid replacement may accumulate and contribute to chronic mild hypohydration (Tanabe et al., 2021). Civil et al. (2019) found that the average 7-day fluid intake of professional ballet dancers was 1.65 ± 0.48 l/day, which is slightly lower than the values found in our study. Given the mounting evidence of both short and long-term detrimental effects of hypohydration on health and well-being (Jéquier & Constant, 2010), guidelines have been established to determine how much water humans require to avoid dehydration and to optimize physical and psychological function. Such daily reference values or adequate intakes range from 2 l/day for women and 2.5 l/day for men from the EFSA, up to 2.7 l/day for women and 3.7 l/day for men from the Institute of Medicine (Gibson et al., 2012).

Relevance of hypohydration for dance performance and injury risk

Even mild hypohydration may have important consequences for dancers, given the high demands on coordination, balance, timing, and neuromuscular control. Studies reveal that mild hypohydration can lead to impaired proprioception and delayed neuromuscular responses, which heighten the risk of acute injuries among dancers, particularly during repetitive or high-impact movements. For example, Long et al. emphasize that neuromuscular conditioning plays a vital role in reducing injury risk and improving functional outcomes in dancers, suggesting that any impairment due to hypohydration could exacerbate injury risks during performances (Long et al., 2021). Hypohydration can disrupt the balance and coordination that dancers rely upon. Clarke et al. (2018) discuss how significant balance capabilities are fundamental to professional dancers, indicating that when hydration is compromised, these capabilities may falter. Given that folk dance involves extensive dynamic movements—such as spins and jumps—optimal hydration is necessary to preserve the intricate balance and coordination essential for these styles. Additionally, proprioception, which is critical for maintaining posture during dynamic movements, may diminish with hypohydration (Hutt & Redding, 2014). This decline could lead to errors in movement execution, as dancers often rely heavily on proprioceptive feedback for positioning and spatial awareness. The reliance on visual inputs can exacerbate the challenges posed by inadequate hydration, potentially leading to performative discrepancies and elevated injury risk, as described by Hutt and Redding, who note how dynamic balance

performance can be affected by variable visual conditions (Hutt & Redding, 2014). Hydration decisions during exercise should account for individual variations in sweat rates, which can be influenced by environmental factors and exercise intensity (Eijsvogels et al., 2013). For instance, studies show that a minimum fluid consumption of 5-7 mL/kg of body mass should be initiated at least four hours before exercise (Li et al., 2024), while fluid consumption rates during exercise should range between 0.15 to 0.34 mL/kg for optimal performance (Holland et al., 2017). This means that a 55 kg female dancer should consume approximately 275-385 ml of fluids \geq 4 hours before training and 0.5-1.12 l/h during 60 minutes of intense exercise. This is critical, since athletes can lose 2-7% of their body weight through sweat, leading to diminished performance levels (Birkemose et al., 2013). The reduction in fluid intake over time may indicate a trend where dancers fail to adjust their hydration habits in response to training loads (Brown et al., 2016). Limited information is available regarding the effects of hypohydration on cognitive function, which is also important for a dancer's performance. In the study by Armstrong et al. (2012), mild hypohydration was produced by intermittent moderate exercise without hyperthermia, and its effects on the cognitive function of women were investigated. A degraded mood, increased perception of task difficulty, lower concentration, and headache symptoms resulted from 1.36% dehydration in females. Although our study did not directly assess cognitive or performance outcomes, the observed hydration patterns may place dancers at risk of reduced precision and increased injury susceptibility.

A drop in fluid intake can lead to behavioral fatigue and decreased adherence to recommendations, which may exacerbate health concerns. Understanding the factors contributing to inadequate hydration and implementing effective strategies to counteract these challenges is essential.

Practical applications and preventive strategies

To address hydration deficits, implementing simple yet effective preventive measures is essential. Scheduled drinking breaks during training can ensure that dancers remain adequately hydrated throughout their routines. Such interventions have been proven effective in promoting positive hydration practices among athletes, thereby enhancing overall performance (Scanlon & Norton, 2024)

There is an urgent need for coaches to understand the importance of hydration. They should be educated about effective hydration strategies and encouraged to create environments that prioritize fluid intake during training. By emphasizing the necessity of staying hydrated, coaches can help their dancers develop healthier hydration habits (Scanlon & Norton, 2024).

Integrating fundamental hydration education into regular training sessions can provide dancers with the knowledge required to make informed decisions about their fluid intake. Educational interventions have been shown to empower athletes to take charge of their hydration needs (Jafari et al., 2019)

These low-cost interventions may be particularly effective in dance settings, where formal sports nutrition support is often limited.

This study has several limitations that should be considered when interpreting the results. First, the relatively small sample size limits the generalizability of the findings. As a result, the findings should be interpreted primarily as exploratory and descriptive, reflecting hydration patterns within a specific collegiate folk-dance ensemble rather than the broader dance population. Second, daily fluid intake was assessed using self-reported fluid intake diaries. Self-reported data are inherently subject to recall bias and social desirability bias, which may have influenced the accuracy of reported fluid intake. Given the context of health-related monitoring, over-reporting of fluid intake appears more likely than under-reporting, as participants may have wished to present their behaviour as compliant with perceived hydration norms. Third, the type of fluids consumed was not standardized across participants. Different beverage types (e.g., plain water, mineral water, or sugar-containing drinks) may influence urine concentration and renal fluid handling differently, potentially affecting USG independently of total fluid volume (Wong et al., 2024). Consequently, variations in fluid composition could partially explain interindividual differences in USG values and limit direct comparison between participants. Fourth, hydration status was assessed using a single biomarker. Although USG is a validated and practical field-based marker, reliance on a single hydration indicator may not fully capture short-term fluctuations in body water balance. In future studies, using methods such as weighing water bottles, weighing athletes before and after exercise, reviewing training diaries, and incorporating bioimpedance measurements could help yield more objective results. Finally, the observational design of our study precludes causal inference.

Conclusions

The present study examined hydration status and daily fluid intake in collegiate folk dancers across two consecutive training microcycles. The results suggest that a significant proportion of dancers may have started training in a state of mild hypohydration. These findings demonstrate that mild hypohydration was prevalent across both sexes and microcycles. Even mild hypohydration may negatively affect physical performance, coordination, attention, and cognitive function, all of which are critical for complex dance movements. Although no cases of severe hypohydration were observed in the present sample. However, the persistent presence of mild hypohydration should not be considered harmless or negligible. Persistent mild hypohydration may accumulate across training days and compromise performance quality, recovery, and injury resilience. The findings highlight the need for greater awareness of hydration practices in dance training environments. Dance coaches and school-based training programs are encouraged to implement basic hydration strategies, such as setting minimum daily fluid intake targets, scheduling regular drinking breaks, and introducing simple hydration monitoring (e.g., urine color charts). These low-cost and easily implementable measures may help reduce the prevalence of hypohydration in dance populations. Future research should explore hydration interventions tailored to the specific demands of dance training.

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Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Attitudes Toward Exercise, Relaxation, and Sleep as Stress Management Strategies among University Undergraduates

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Abstract

Poorly managed stress can be detrimental to health. However, exercise, relaxation, and sleep are important strategies that can be adopted to manage stress and prevent its negative health consequences. This study investigated attitudes toward exercise, relaxation, and sleep as stress management strategies among undergraduates. A total of three hundred and fifty-five (355) undergraduates from the University of Nigeria participated in the cross-sectional study. The instrument used for data collection was a researcher-designed questionnaire developed based on reviewed related literature (Carver, 1997; Smith, 2002). The reliability of the instrument was confirmed with Cronbach's alpha coefficients of 0.8. The major findings showed that undergraduates of University of Nigeria Nsukka had a positive attitude ($\bar{X}=3.43$, $SD=0.52$) towards exercise ($\bar{X}=0.72$, $SD=0.93$), relaxation ($\bar{X}=3.95$, $SD=0.55$) and sleep ($\bar{X}=3.47$, $SD=0.78$) for managing stress. The results also revealed that there was no significant difference in the attitude towards exercise, relaxation and sleep based on gender ($t=-1.487$, $P=0.138$). Exercise ($t=0.929$, $P=0.353$), relaxation ($t=-4.057$, $P=0.000$) and sleep ($t=-0.619$, $P=0.536$), and age ($t=1.115$, $P=0.326$). Exercise ($t=0.621$, $P=0.535$), relaxation ($t=1.414$, $P=0.158$) and sleep ($t=0.014$, $P=0.989$). The study concluded that undergraduates have a positive attitude towards exercise, relaxation, and sleep as stress management strategies among university undergraduates. Furthermore, the study concluded that females showed more favourable attitudes toward relaxation as a stress management strategy compared to males.

Keywords: health, life-style behaviours, students, health beliefs, coping mechanisms

Introduction

University life is often characterised by high academic demands, social adjustments, and personal development challenges, all of which can lead to significant stress among students (Fentahun et al., 2025). Stress is a state of worry or mental tension caused by a difficult situation (World Health Organisation [WHO], 2023). Although stress is a normal part of life and can even be motivating in certain contexts (Robotham & Julian, 2006), high levels of stress pose a threat to health

(Cohen et al., 2019). As such, the importance of developing effective coping strategies for stress management among undergraduate students cannot be overstated. Among the many approaches to managing stress, lifestyle behaviours such as adequate sleep, relaxation techniques, and regular exercise are recognised as effective and sustainable strategies (American College Health Association [ACHA], 2020).

Exercise has been widely documented as a beneficial tool in stress reduction. Exercise is known to reduce levels of corti-

sol, the body's primary stress hormone, while stimulating the production of endorphins, neurotransmitters that improve mood and promote a sense of well-being (Salmon, 2001). Regular participation in moderate to vigorous exercise has been associated with lower levels of perceived stress among university students (Nguyen-Michel et al., 2006). However, the extent to which students perceive and utilise exercise as a stress management tool can be influenced by individual attitudes, awareness, and access to resources.

Furthermore, relaxation practices, including mindfulness, meditation, breathing techniques, and progressive muscle relaxation, are increasingly recognised as effective in reducing psychological distress and enhancing mental clarity (Grossman et al., 2004). These techniques work by activating the parasympathetic nervous system, which counters the body's stress response and helps induce a state of calm. Despite their documented benefits, relaxation strategies are often underutilised by students, possibly due to a lack of knowledge or perceived difficulty in maintaining consistency (de Vibe et al., 2013).

Sleep, an essential component of overall health, also plays a critical role in stress regulation (Lund et al., 2010). Poor sleep quality and insufficient sleep duration have been consistently linked with increased stress, anxiety, and depression in student populations (Lund et al., 2010). A good night's sleep helps regulate emotional reactivity and cognitive function, which are vital for managing academic and social pressures (Fentahun et al., 2025). Nevertheless, many students compromise sleep in favour of academic demands or social activities, thereby exacerbating stress levels.

Recent research (Fentahun et al., 2025; Liu et al. 2025) highlights the importance of health behaviours such as exercise, sleep, and relaxation in stress management among university students. A systematic review and meta-analysis (Liu et al., 2025) demonstrated that physical exercise interventions significantly improve university students' mental health outcomes, including reductions in stress, anxiety, and depression, while enhancing wellbeing and sleep quality; aerobics, resistance, and high-intensity exercises showed notable benefits when performed regularly over extended periods. Another Chinese cross-sectional study (Xu et al., 2025) found that higher levels of physical activity were associated with better sleep quality among university students, mediated by reductions in rumination and depression, suggesting that exercise helps regulate psychological processes that contribute to sleep disturbances in stressed students. Furthermore, recent work has identified significant associations between students' well-being, sleep patterns, sport participation, and perceived stress, with better sleep and higher physical activity levels linked to improved well-being and lower stress.

Rationale of the study

Despite growing evidence that physical exercise and relaxation practices can mitigate stress and improve sleep quality in university populations, few studies concurrently assess students' attitudes toward these stress management strategies alongside self-reported use and perceived effectiveness. Most existing work focuses on behavioural outcomes or intervention effects rather than on attitudinal constructs such as the

value students place on exercise, relaxation, and sleep for coping with stress. Additionally, research tends to examine these coping mechanisms in isolation rather than as an integrated set of stress management strategies.

In Nigeria, stress among university students is a growing concern, particularly as institutional and societal pressures mount. A study by Eze and Eze (2016) found that many Nigerian undergraduates experience high levels of stress due to academic workloads, financial concerns, and future uncertainties. However, little research has specifically examined how Nigerian students perceive and engage in health-promoting behaviours like exercise, relaxation, and sleep for managing stress. Understanding these attitudes is essential for developing targeted interventions to promote holistic well-being among students.

This study, therefore, investigated the attitudes of undergraduate students at the University of Nigeria, Nsukka, toward exercise, relaxation, and sleep as strategies for managing stress based on demographic variables of age, gender and marital status. We hypothesised that there is no significant difference in attitudes towards exercise, relaxation and sleep as stress management strategies based on gender, age and marital status.

Methods

Study design and setting

A cross-sectional study was conducted between May and July 2024 at the University of Nigeria, Nsukka, a large federal public university located in Enugu State, southeastern Nigeria. The university hosts a diverse undergraduate population drawn from various academic disciplines, making it an appropriate setting for examining stress management attitudes among undergraduates.

Participants

The participants comprised undergraduates from different academic departments. The participants were undergraduate students drawn from various academic departments. The sample comprised 181 males and 174 females. With respect to age distribution, 303 participants were aged 16–24 years, while 52 participants were aged 25–34 years. Participants were adequately informed about the aims and procedures of the study, and written informed consent was obtained from all participants before data collection.

Sampling strategy

A sample size of 355 respondents participated in the study. A multistage sampling technique was used in this study. In the first stage, simple random sampling (balloting without replacement) was used to select seven faculties from the nine faculties at the University of Nigeria, Nsukka. In the second stage, three departments were randomly selected from each of the seven selected faculties, also using simple random sampling by balloting without replacement, resulting in a total of 21 departments. In the third stage, 18 undergraduate students were recruited from each of the 21 selected departments us-

ing a convenience sampling technique, based on availability and willingness to participate. This procedure yielded a total of 378 undergraduates. After data collection and cleaning, 355 questionnaires, which represent 94 per cent of the sample, were duly completed and therefore used for analysis.

Measures

Data was collected using a researcher-designed questionnaire developed based on information from reviewed related literature (Carver, 1997; Smith, 2002). The questionnaire was made up of four sections. Section A contained three (3) items which elicited information on the socio-demographic variables (age, gender and marital status). Section B consisted of five (5) items, which sought information on the attitude towards exercise. Section C consisted of seven (7) items, which sought information on the attitude towards relaxation. Section D consisted of four (4) items, which sought information on the attitude towards sleep. The questions were assigned a four-point Likert response format of Strongly Agreed (4 points), 'Agree (3 points)', 'Disagree (2 points)', and 'Strongly Disagree (1 point)' (Boone & Boone, 2012). Mean and standard deviation were used for analysing the Likert scale questions, which measured attitude. Mean scores from 2.5 and above were rated as a positive attitude, while a score below 2.5 was rated as a negative attitude.

To examine the face and content validity, the questionnaire was given to a professional board of five experts on the subject (medical and public health sciences, human kinetics and sports studies) and an expert in methodology. After collecting the opinions of these experts, possible modifications were made.

To determine the reliability of the questionnaire, Cronbach's alpha was adopted. This yielded a score of 0.82. The cut-off point for the calculations was 0.70.

Data collection procedure

This study was approved by the Research Ethics Committee of the Faculty of Education, University of Nigeria, Nsukka (Ethical Clearance Code; UNN/FE/REC24/092), and was conducted in compliance with the Ethical Principles of the World Medical Association Declaration of Helsinki for medical research involving human subjects (World Medical Association, 2013).

To facilitate data collection, the research team met with the Heads of Departments of the several departments selected for the study to ask for their consent to study their subjects to secure the respondents' cooperation. Following agreement with the department Heads, the students gave their informed consent verbally after being briefed on the procedure and timing of the data collection. Additionally, the research team informed the participants of the study's goals and gave them assurances regarding the confidentiality of their personal information.

Ten research assistants aided in the data collection. These assistants were undergraduate students from various departments at the University of Nigeria, Nsukka—an approach intended to encourage cooperation from the respondents. A total of 378 questionnaires were distributed to the respondents by the researcher and the assistants. However, 355 had complete data and were included in the subsequent analyses.

Data analysis

Data were analysed using the Statistical Package for the Social Sciences (SPSS, Version 25; IBM Corp., Armonk, NY, USA).

The null hypotheses were tested using an independent t-test and One-way ANOVA. The Independent T test was used to compare male and female attitudes towards exercise, relaxation and sleep as stress management. The Independent T test was also used to compare attitudes based on age. While One-way ANOVA was used to compare singles, married and separated participants' attitudes towards exercise, relaxation and sleep as stress management. The entire null hypotheses were tested at a 0.05 level of significance. All tests were 2-tailed, and probability values less than or equal to 0.05 ($p \leq 0.05$) were considered significant. We also conducted Scheffe Post Hoc Analysis of Group Mean Difference to compare the mean difference between single, married and separated undergraduates and their attitude towards using sleep as a stress coping strategy.

Results

The undergraduates reported an overall positive attitude toward exercise, relaxation, and sleep as stress management strategies ($\bar{X}=3.43$, $SD=0.52$). Specifically, attitudes toward exercise were moderate ($\bar{X}=2.72$, $SD=0.93$), while attitudes toward relaxation ($\bar{X}=3.95$, $SD=0.55$) and sleep ($\bar{X}=3.47$, $SD=0.78$) were more positive (Table 1).

Table 1. Attitude towards exercise, relaxation and sleep as stress management among undergraduates of University of Nigeria Nsukka (n=355)

S/N	Items	M	SD	Decision
Exercise				
1	Whenever I feel stressed out, I mostly exercise	2.69	1.33	PA
2	Engaging in weightlifting to get relief from stress	2.38	1.21	NA
3	Participating in outdoor games when I feel stressed or anxious	3.16	1.32	PA
4	Swimming so as to manage stress	2.65	1.29	PA
5	Cycling to get relief when confronted with a stressful situation	2.72	1.24	PA

(continued from previous page)

Table 1. Attitude towards exercise, relaxation and sleep as stress management among undergraduates of University of Nigeria Nsukka (n=355)

S/N	Items	M	SD	Decision
Relaxation				
6	Taking a deep breath whenever I'm under pressure	4.41	0.78	PA
7	Isolating into a peaceful state when feeling threatened	4.23	0.92	PA
8	Having a warm bath is stress relieving for me	3.87	1.10	PA
9	Casting my mind on a pleasant event when stressed	3.92	1.08	PA
10	Meditating whenever I experience stress	3.63	1.09	PA
11	Getting a massage when stressed	3.23	1.24	PA
12	Listening to music when stressed	4.34	0.92	PA
Sleep				
13	Sleeping often whenever stressed or anxious	4.13	1.10	PA
14	Sleeping more when nervous or under pressure	3.48	1.28	PA
15	Staying awake all night thinking about stressful events	2.76	1.36	PA
16	Sleeping up to eight hours is stress relieving	3.52	1.38	PA
Overall Attitude		3.43	0.52	PA

Positive attitude towards exercise, relaxation and sleep for managing stress = $\bar{X} > 2.50$
 Negative attitude towards exercise, relaxation and sleep for managing stress = $\bar{X} < 2.50$

There was no significant difference in attitudes toward exercise ($t = -1.487, p = 0.138$) and sleep ($t = -1.487, p = 0.138$) based on gender, although male students scored slightly higher than female students in both cases. In contrast, there

was a significant difference in attitudes toward relaxation based on gender ($t = -4.057, p < 0.001$), with male students showing more positive attitudes toward relaxation than female students (Table 2).

Table 2. Summary of t-test analysis showing the difference in attitude towards exercise, relaxation and sleep as Stress Management among Undergraduates of University of Nigeria, Nsukka Enugu State based on Gender (n=355)

Variable	Male		Female		t	p	Cohen's d
	Mean	SD	Mean	SD			
Exercise	2.77	0.94	2.67	0.93	0.929	0.353	0.11
Relaxation	3.83	0.58	4.06	0.50	-4.057	0.000	-0.43
Sleep	3.45	0.75	3.50	0.80	-0.619	0.536	-0.06
Overall Attitude	3.39	0.53	3.48	0.51	-1.487	0.138	-0.17

Note. NS = Not Significant; S = Significant; SE = Standard Error; CI = Confidence Interval

Regarding age, there were no significant differences in attitudes toward exercise, relaxation, or sleep ($t = 1.115, p = 0.326$), though students aged 16–24 years had slightly

higher mean scores for exercise and sleep than those aged 25–34 years (Table 3).

Table 3. Summary of t-test analysis showing the difference in attitude towards Exercise, Relaxation and Sleep as stress management among Undergraduates of University of Nigeria, Nsukka Enugu State based on age (n=355)

Variable	Younger (16–24 y)		Older (25–34 y)		t	p	Cohen's d
	Mean	SD	Mean	SD			
Exercise	2.73	0.93	2.65	0.99	0.621	0.535	0.08
Relaxation	3.96	0.57	3.85	0.45	1.414	0.153	0.21
Sleep	3.47	0.76	3.47	0.88	0.014	0.989	0.00
Overall Attitude	3.45	0.53	3.37	0.49	0.984	0.326	0.16

Note. NS = Not Significant; SE = Standard Error; CI = Confidence Interval

Analysis by marital status indicated no significant differences in attitudes toward exercise ($F=1.556$, $p=0.212$) and relaxation ($F=1.556$, $p=0.212$). However, there was a significant difference in attitudes toward sleep as a stress manage-

ment strategy ($F=4.279$, $p=0.015$), with married students reporting the most positive attitudes, followed by separated students, and single students reporting the least positive attitudes (Table 4).

Table 4. One-way ANOVA testing the difference in attitude towards exercise, relaxation and sleep as stress management among undergraduates of University of Nigeria, Nsukka based on marital status (n=355)

Variable	Married		Separated		Single		F	p	Post-hoc
	Mean	SD	Mean	SD	Mean	SD			
Exercise	3.20	0.98	2.63	0.83	2.70	0.93	1.802	0.167	NS
Relaxation	3.84	0.66	4.14	0.45	3.95	0.55	0.641	0.527	NS
Sleep	3.46	0.76	3.04	1.22	3.46	0.76	4.279	0.015	NS
Overall Attitude	3.43	0.52	3.38	0.60	3.43	0.52	1.556	0.212	NS

Note. NS = Not Significant; S = Significant at $p<0.05$

Post hoc comparisons confirmed that single students had significantly lower mean scores for sleep compared with married students, whereas married students had significantly

more positive attitudes than separated students. There was no significant difference between single and separated students in their attitudes toward sleep (Table 5).

Table 5. Scheffe Post Hoc analysis of group mean difference based on attitude towards exercise, relaxation and sleep as stress management among undergraduates of University of Nigeria, Nsukka (n=355)

(I) Marital	(J) Marital	Mean Difference (I–J)	SE	p	95% CI Lower	95% CI Upper
Single	Married	-0.560	0.217	0.037	-1.094	-0.259
Single	Separated	0.417	0.317	0.420	-0.361	1.196
Married	Single	0.560	0.217	0.037	0.026	1.094
Married	Separated	0.978	0.379	0.037	0.045	1.910
Separated	Single	-0.417	0.317	0.420	-1.196	0.361
Separated	Married	-0.978	0.379	0.037	-1.910	-0.045

The mean difference is significant at the 0.05 level

Discussion

The findings of our study indicate that undergraduates at the University of Nigeria, Nsukka, generally hold positive attitudes toward exercise, relaxation, and sleep as strategies

for managing stress ($\bar{X}=3.43$, $SD=0.52$). Among the three strategies, attitudes toward relaxation were the most positive ($\bar{X}=3.95$, $SD=0.55$), followed by sleep ($\bar{X}=3.47$, $SD=0.78$), while attitudes toward exercise were moderate ($\bar{X}=2.72$, $SD=0.93$). These findings suggest that students may prefer

stress management strategies that are immediately accessible, require less physical exertion, and can be integrated easily into daily routines.

The high preference for relaxation techniques aligns with previous research (Sharma et al., 2015) indicating that strategies such as deep breathing, mindfulness, and leisure activities are widely accepted among university students due to their calming effects and ease of practice (Sharma et al., 2015). Relaxation can reduce sympathetic nervous system activity, lower cortisol levels, and enhance emotional regulation, providing immediate stress relief (Khoury et al., 2015; Tang et al., 2007). The moderately high rating for sleep found in our study is consistent with literature emphasizing its role in psychological recovery, cognitive functioning, and emotional regulation (Pilcher & Huffcutt, 1996; Walker, 2017). Adequate sleep has been shown to improve attention, mood, and resilience to stress, which may explain why students recognize it as an effective coping strategy.

Conversely, exercise received the lowest mean score, indicating a relatively less positive attitude toward physical activity for stress management. This contrasts with abundant evidence demonstrating the benefits of exercise for reducing stress, anxiety, and depressive symptoms (Biddle & Asare, 2011; Salmon, 2001; Sharma et al., 2006). The lower enthusiasm for exercise in this sample may reflect perceived barriers such as time constraints, physical fatigue, or lack of accessible facilities (Saxena et al., 2015). Cultural and environmental factors, including academic workload and campus infrastructure, may also influence students' willingness to engage in physical activity as a coping mechanism.

Regarding gender differences, our study found no significant differences in attitudes toward exercise and sleep. However, there was a significant difference in attitudes toward relaxation, with male students demonstrating more positive attitudes than female students. Interestingly, this contrasts with some studies suggesting that females are generally more likely to engage in psychological coping strategies, including relaxation and social support (Matud, 2004; Tamres et al., 2002). This discrepancy could be explained by cultural or contextual factors specific to the study population, such as gendered perceptions of stress management or differential exposure to relaxation-promoting activities. It may also reflect variations in stressor types experienced by male and female students, with males potentially adopting relaxation techniques more actively to cope with academic or social pressures.

Age did not significantly influence attitudes toward any of the stress management strategies. This finding suggests that within the undergraduate population, stress-coping attitudes may be relatively stable across the typical age range of 16–34 years. This aligns with previous research by Eze and Eze (2016) indicating that coping preferences in young adults are more strongly influenced by individual personality traits, situational demands, and perceived efficacy of strategies rather than chronological age (Eze & Eze, 2016; Folkman & Moskowitz, 2004).

Marital status significantly influenced attitudes toward sleep, with married students reporting the most positive attitudes, followed by separated students, and single students

reporting the least positive attitudes. This may be due to structured routines and shared responsibilities in married life, which encourage regular sleep patterns and reinforce the value of restorative behaviors (Troxel et al., 2007). In contrast, single students may experience more irregular schedules or heightened academic and social stress, reducing attention to sleep as a coping mechanism. Separated students' lower scores may reflect relational stress or emotional instability impacting sleep quality (Meijer, 2008; Troxel et al., 2007).

The findings of this study may also be influenced by environmental and cultural factors specific to the Nigerian context. For instance, high academic workload, limited recreational facilities, and cultural norms surrounding exercise and leisure may shape students' attitudes toward various coping strategies. The preference for relaxation and sleep over exercise may also be related to perceived convenience, immediate effectiveness, and personal enjoyment, which are known to predict engagement in coping behaviors (Schunk & DiBeneditto, 2020).

Our study has several strengths, including its broad focus on multiple stress management strategies, the inclusion of demographic comparisons, and the use of a large, diverse undergraduate sample, enhancing the reliability of its findings. However, limitations include the use of self-reported data, which may be subject to social desirability bias, the single-institution sample, limiting generalizability, and the cross-sectional design, which precludes causal inference. Future research should consider longitudinal or multi-institutional designs, as well as qualitative methods to explore underlying motivations and barriers influencing students' attitudes. Intervention-based studies could further promote positive coping strategies, particularly in areas where attitudes toward certain strategies, such as exercise, are less favourable.

Conclusion

Overall, the results of this study suggest that undergraduates at the University of Nigeria, Nsukka, hold generally positive attitudes toward exercise, relaxation, and sleep as effective strategies for managing stress. However, notable variations exist based on demographic factors, particularly gender and marital status, with females showing more favourable attitudes toward relaxation, and married students demonstrating more positive attitudes toward sleep compared to their single or separated peers. These findings highlight the importance of understanding how personal characteristics influence coping preferences, which can inform the development of more targeted and effective stress management interventions. To enhance their impact, such interventions should be accessible and tailored to address the unique needs of different student groups. By promoting balanced and sustainable coping strategies across diverse populations, universities can play a critical role in improving students' mental health, academic performance, and overall well-being.

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Conflict of interest

The authors have declared no competing or conflicting interests.

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Examining Qualitative Changes in Physical Fitness and Body Composition in a School-Based Physical Literacy Intervention: Methodological and Practical Considerations

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Abstract

Studying qualitative changes is important in sport and exercise sciences because it reveals how different physical traits interact and develop together over time. This study aimed to explore how a physical literacy-based intervention (PL-intervention) affects the relationships between body composition and fitness indicators in preadolescent children. The participants were 112 children (9 to 11 years old, 50 girls), divided into a control group (C group, n=61) and an experimental intervention group (E group, n=51). They were tested in anthropometrics/body composition (height, mass, body fat, and skeletal muscle mass) and fitness indicators (assessing jumping power, abdominal and upper body strengths, mobility, flexibility, and cardiovascular endurance) at initial (September), final (December), and retention measurements (May). Between the initial and final measurements, the E-group participated in a structured physical literacy-based intervention (PL-intervention) delivered as a part of their regular physical education classes (PE), while the C-group participated in standard PE. To examine changes in the intervariable associations over time, correlation matrices were computed, while factor loading matrices were compared across measurement phases using Tucker's coefficient of congruence for each study group. During the course of the study, the C-group experienced certain qualitative changes, showing early signs of structural divergence. On the other hand, factor structures and correlations among variables for the E-group were similar across measurements, suggesting that the intervention helped maintain stable relationships between body composition and physical fitness variables. The results suggest that the applied intervention program supported coordinated and balanced physical development and showed that such programs may help children develop lasting and organized patterns of physical functioning.

Keywords: curriculum, anthropometry, motor abilities, physical education, program evaluation

Introduction

Preadolescence is a critical developmental period marked by rapid physical, cognitive, and social changes (Rowland, 2005). During this stage, monitoring physical fitness and body composition is essential, as it provides valuable insight into children's overall health trajectories and poten-

tial risk factors for chronic diseases (Rajković Vuletić et al., 2024). Global trends continue to show a rising prevalence of overweight and obesity in children, often linked to sedentary behavior, insufficient physical activity, and poor dietary habits (Masanović et al., 2020). These issues are associated with serious physical health outcomes, including insulin resistance,

increased cardiovascular risk, and orthopedic complications. Additionally, there is growing evidence that excess weight and low physical fitness are related to psychosocial difficulties, such as low self-esteem and reduced academic performance (Santana et al., 2017)

Low levels of physical fitness are recognized as strong predictors of future health, independent of body weight. Meanwhile, among children and adolescents, physical activity is the most important determinant of physical fitness (Lohman et al., 2008). Given that both physical activity and fitness levels tend to track from childhood into adolescence and adulthood, early identification and timely intervention are crucial. Schools and sports programs have therefore been recognized as key environments for promoting healthy behaviors and monitoring fitness trends (Marinho et al., 2022). As a result, many studies have examined fitness trends and the effectiveness of various school-based or sport-related fitness programs in pediatric populations (Rauner, Mess, & Woll, 2013). However, most of these studies focus primarily on quantitative changes evidencing improvements in absolute values of body composition or fitness indices (e.g., cardiorespiratory endurance, strength, power, flexibility) (Errisuriz, Golaszewski, Born, & Bartholomew, 2018; Kriemler et al., 2011)

While such metrics are fundamental for evaluating intervention effects and understanding growth patterns, they represent only one side of the adaptation process. In contrast, qualitative changes refer to shifts in the internal structure of relationships between variables (i.e., how fitness and body composition measures interact and reorganize over time). For example, two children may both show improved results in a beep test (commonly used to assess aerobic capacity), yet the underlying factors driving this improvement could differ, such as increased step length from growth, gains in muscular power, or enhanced cardiovascular function (Rowland, 2005). Qualitative analysis seeks to uncover these interactions and reveal how and why performance changes occur by examining the evolving relationships among the contributing variables. From the developmental perspective, this is highly important because functional improvements may take place without major changes in variable structure — and vice versa. Therefore, a research focus on qualitative structure could provide a more comprehensive understanding of adaptation and physical development.

In other words, analyzing qualitative changes allows researchers and practitioners to “look beyond outcome measures” and investigate how a system as a whole adapts. In this context, it involves evaluating whether specific fitness and body composition variables become more or less connected over time, whether associations between variables strengthen or weaken, and whether new relationships emerge. These structural changes may reflect underlying shifts in motor control, neuromuscular coordination, or metabolic function, all of which are important for long-term health and physical competence. For instance, if improved aerobic capacity becomes increasingly related to lean muscle mass rather than just reduced fat mass, it may indicate a more efficient or robust physiological adaptation. Methodologically, such insights can be gained by comparing correlation matrices or factor struc-

tures of selected variables across different time points (e.g., before and after the intervention). These methods can also detect delayed or latent effects that may not be visible through performance outcomes alone. Ultimately, qualitative analysis offers a deeper understanding of adaptation mechanisms, durability of change, and individual variability in response to physical education and training.

In recent years, physical literacy has emerged as a promising framework for promoting lifelong engagement in physical activity and, in turn, supporting fitness development (Carl et al., 2023; Gilic, Sekulic, Munoz, Jaunig, & Carl, 2025; Lilic et al., 2024; Rajkovic Vuletic et al. 2026). In general, physical literacy goes beyond physical competence alone; it incorporates motivation, confidence, knowledge, and understanding of movement, encouraging children to value and maintain active lifestyles (Kestic et al., 2022; Sunda et al., 2022; Whitehead, 2013). Because childhood is a sensitive period for both motor development and behavior formation, physical literacy-based interventions can play a key role. Unlike traditional programs that often target isolated physical capacities, physical literacy emphasizes the development of coordinated, adaptable movement patterns that may help sustain long-term functional balance. As such, physical literacy interventions have the potential to support not only measurable performance gains but also the stability and reorganization of deeper structural dimensions related to body composition and fitness.

Studies have frequently examined the quantitative effects of physical literacy interventions and have shown promising results (Carl et al., 2022; Rajkovic Vuletic et al., 2026). However, there is an evident lack of studies that have evidenced structural/qualitative changes in specific variables as a result of physical literacy intervention in children. Therefore, the aim of this study was to investigate how a physical literacy-based intervention influences the relationships between body composition and physical fitness in preadolescent children. Specifically, the study explored whether the intervention led to qualitative changes by comparing structural relationships over time between an experimental group and a control group. Through this approach, we aimed to assess whether physical literacy education supports more coordinated and enduring physical development.

Methods

Participants

The sample of participants consisted of 112 preadolescent children (50 girls) from southern Croatia. At the time of data collection, the participants were between 9 and 11 years old and were enrolled in either the 3rd (n=71) or 4th grade (n=48) of elementary school (two schools in total). All the children were in good health and attended physical education (PE) classes on a regular basis. Those who had been ill or who had sustained a musculoskeletal injury within two weeks prior to testing were excluded. Before participation, parents or legal guardians were informed about the study objectives and procedures, and parental written consent was obtained. The research protocol was preapproved by the Ethics Committee of the Faculty of Kinesiology, University of Zagreb. The total

sample was divided into a control group (n=60) and an experimental group (n=52) similarly across both schools included in the study.

Variables

Variables included a set of anthropometric/body composition indices and a set of physical fitness tests.

Anthropometrics included body height (measured by stadiometer in 0.5 cm) and body mass (measured in 0.1 kg by Tanita measuring scale). Body composition measures included body fat and skeletal muscle mass (both in % of body mass) by a bioelectrical impedance analyzer (Tanita TBF-300, Tokyo, Japan).

Physical fitness (PF) was assessed using selected tests evaluating aerobic endurance, muscular strength and endurance (abdominal and upper body), torso extensor strength and flexibility, overall flexibility, and jumping power. Aerobic endurance was measured using the 15-meter multistage fitness test (Beep test), which includes 21+ levels, each consisting of multiple 15-meter running intervals. Participants ran between two cones, turning and touching the line at each beep. The test ended when they could no longer reach the line in time; the final score reflected the highest level completed. Upper body strength and endurance were evaluated using the push-up test (Push-ups). From a plank position, participants lowered themselves until elbows reached a 90° angle and then returned to full extension while maintaining a straight body

line. The number of correctly performed repetitions was recorded. Abdominal strength and endurance were assessed using the sit-up test (Sit-ups), where participants performed as many correct sit-ups as possible (up to a maximum of 75). Each correctly executed repetition was scored. Torso extensor strength and flexibility were measured with the torso lift test (Torso lift), in which participants raised their upper back (cervical and thoracic spine) from the floor to the maximum controllable height, keeping the head aligned with the spine. Flexibility of the lower back and hamstrings was assessed using the sit-and-reach test (Sit-reach). Seated with legs extended, participants reached forward along a measuring box, holding the position for at least two seconds. The best of three trials was used. The explosive strength was measured with the standing long jump test (broad jump). Participants jumped forward barefoot from a standing position onto a standardized mat (ELAN, Begunje, Slovenia), and the best of three jumps (in centimeters) was recorded.

Intervention

Participants were assessed at three time points: initial measurement (September 2024), final measurement (late December 2024), and retention measurement (May 2025). The intervention was conducted between the initial and final assessments. An overview of the study timeline is presented in Figure 1.

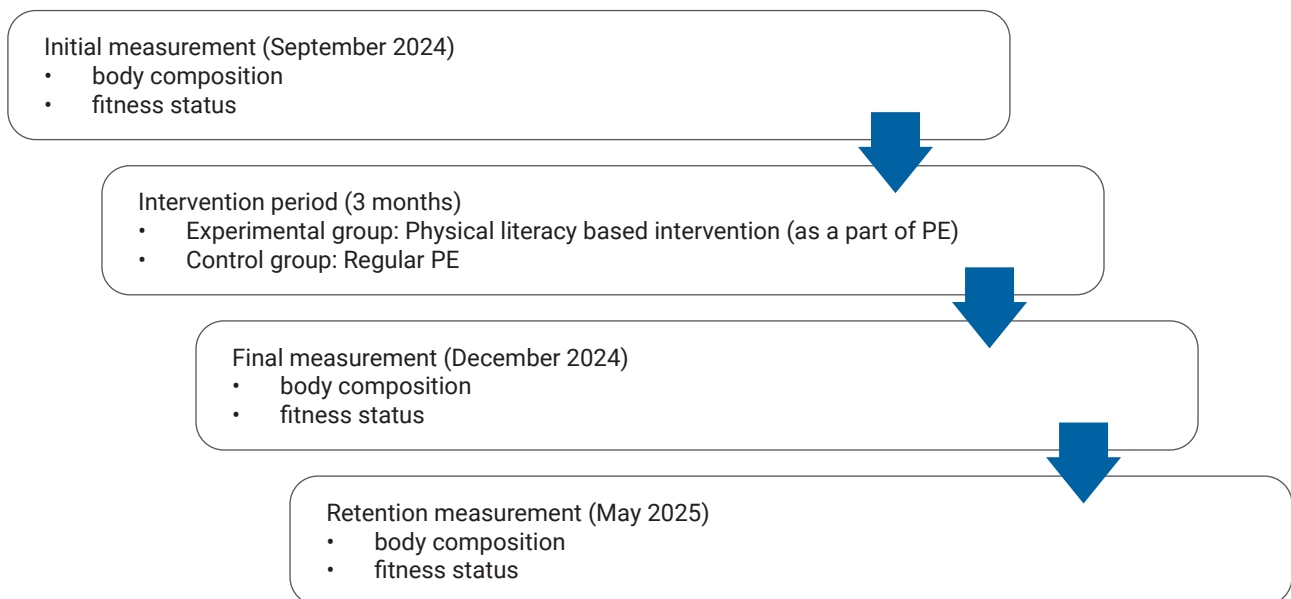


Figure 1. Timeline of the study

The educational intervention, focused on physical literacy (PL), was implemented within the existing PE schedule for the experimental group over a 12-week period. During this time, students received three PE sessions weekly, amounting to a total of 36 lessons. The intervention incorporated 12 short, original educational videos (3–4 minutes each), each addressing a key topic related to PL or physical health. The video content was organized into the following themes: two videos covered core PL principles (e.g., movement motiva-

tion, confidence, and understanding), three focused on cardiorespiratory fitness, five targeted motor abilities (strength, power, coordination, flexibility), and two addressed general health habits, including nutrition. Each video was shown three times to reinforce learning and ensure knowledge retention. More details on educational intervention and video materials are available elsewhere (please see supplementary materials in published study of Rajkovic Vuletic et al., 2026).

Statistics

To examine changes in the intervariable relationships over time, correlation matrices were computed for each measurement phase within both the control and experimental groups. Jennrich’s test was used to statistically assess differences between correlation matrices obtained from repeated measurements on the same participants (Jennrich, 1970; Steiger, 1980).

To assess the stability and reorganization of latent factor structures, exploratory factor analysis was performed using the Varimax rotation method and the Guttman–Kaiser criterion for factor extraction (Kaiser, 1958). Factor loading matrices were compared across measurement phases using Tucker’s coefficient of congruence (Lorenzo-Seva & Ten Berge, 2006). Congruence values above 0.85 were interpreted as reflecting

good structural similarity, while values above 0.95 indicated near-identity. In comparisons involving a different number of factors across phases (e.g., 3 vs. 2), only the leading shared number of factors was compared to ensure interpretability. All matrix and factor comparisons were conducted separately for the control and experimental groups to determine the extent to which the intervention influenced structural stability or reorganization.

Results

Table 1 presents the Pearson’s correlation coefficients calculated between study variables in the initial, final and retention measurements for the control group. Meanwhile, correlations between study variables for the experimental group are shown in Table 2.

Table 1. Correlations between study variables in the initial, final, and retention measurements for the control group (*denotes significance of p<0.05)

		1	2	3	4	5	6	7	8	9
Broad jump (1)	Initial	-								
	Final	-								
	Retention	-								
Push-ups (2)	Initial	0.47*								
	Final	0.41*								
	Retention	0.44*								
Sit-ups (3)	Initial	0.32*	0.28*							
	Final	0.42*	0.47*							
	Retention	0.32*	0.33*							
Trunk lift (4)	Initial	0.04	0.04	0.11						
	Final	0.18	-0.05	-0.12						
	Retention	0.13	0.05	0.14						
Sit-reach (5)	Initial	0.08	0.05	0.33*	0.15					
	Final	0.16	0.11	0.13	0.31*					
	Retention	0.14	0.03	0.18	0.29*					
Beep test (6)	Initial	0.51*	0.51*	0.17	0.13	-0.16				
	Final	0.23*	0.17	0.10	0.00	-0.10				
	Retention	0.10	0.05	-0.08	-0.22*	-0.05				
Height (7)	Initial	0.06	-0.41*	0.13	0.02	0.16	-0.23*			
	Final	0.12	-0.35*	-0.05	0.24*	0.20	0.04			
	Retention	-0.03	-0.41*	-0.01	-0.04	0.10	0.11			
Mass (8)	Initial	-0.37*	-0.42*	-0.18	0.05	-0.07	-0.28*	0.43*		
	Final	-0.36*	-0.45*	-0.35*	0.18	0.05	-0.15	0.64*		
	Retention	-0.41*	-0.48*	-0.28*	0.01	0.05	-0.03	0.65*		
Body fat (9)	Initial	-0.70*	-0.52*	-0.26*	0.10	0.10	-0.52*	0.19	0.64*	
	Final	-0.63*	-0.44*	-0.41*	0.12	0.08	-0.24*	0.23*	0.81*	
	Retention	-0.17	-0.09	-0.09	0.03	0.02	-0.06	0.12	0.26*	
Muscle mass (10)	Initial	0.70*	0.52*	0.26*	-0.10	-0.10	0.51*	-0.19	-0.64*	-0.98*
	Final	0.63*	0.44*	0.41*	-0.12	-0.09	0.24*	-0.23*	-0.81*	-0.98*
	Retention	0.65*	0.45*	0.29*	-0.09	-0.21*	0.12	-0.19	-0.75*	-0.33*

Table 2. Correlations between study variables in the initial, final, and retention measurements for the experimental group (*denotes significance of p<0.05)

		1	2	3	4	5	6	7	8	9
Broad jump (1)	Initial	-								
	Final	-								
	Retention	-								
Push-ups (2)	Initial	0.54*								
	Final	0.31*								
	Retention	0.60*								
Sit-ups (3)	Initial	0.30*	0.39*							
	Final	0.46*	0.25							
	Retention	0.48*	0.26							
Trunk lift (4)	Initial	0.36*	0.11	0.23						
	Final	0.08	0.07	0.02						
	Retention	0.19	-0.05	0.26						
Sit-reach (5)	Initial	0.16	0.04	0.20	0.42*					
	Final	0.18	-0.12	0.20	0.37*					
	Retention	0.24	-0.10	0.36*	0.46*					
Beep test (6)	Initial	0.55*	0.47*	0.25	0.20	-0.09				
	Final	0.60*	0.34*	0.37*	-0.03	-0.02				
	Retention	0.57*	0.71*	0.41*	0.04	-0.17				
Height (7)	Initial	-0.19	-0.41*	0.26	0.28	0.29	-0.10			
	Final	-0.28*	-0.12	0.17	0.26	0.24	-0.27*			
	Retention	-0.31*	-0.46*	0.07	0.28	0.24	-0.46*			
Mass (8)	Initial	-0.36*	-0.45*	0.16	0.07	0.16	-0.34*	0.78*		
	Final	-0.44*	-0.13	-0.01	0.33	0.09	-0.44*	0.83*		
	Retention	-0.44*	-0.43*	-0.17	0.19	0.07	-0.55*	0.80*		
Body fat (9)	Initial	-0.49*	-0.60*	-0.07	-0.07	0.12	-0.54*	0.45*	0.82*	
	Final	-0.65*	-0.21	-0.29*	0.33*	0.18	-0.61*	0.62*	0.82*	
	Retention	-0.48*	-0.56*	-0.25	0.13	0.16	-0.65*	0.58*	0.85*	
Muscle mass (10)	Initial	0.22	0.40*	-0.05	-0.29*	-0.27*	0.37*	-0.40*	-0.48*	-0.55*
	Final	0.62*	0.20	0.22	-0.34*	-0.11	0.63*	-0.63*	-0.86*	-0.96*
	Retention	0.48*	0.55*	0.25	-0.13	-0.16	0.65*	-0.58*	-0.85*	-0.98*

In the control group, the comparison between the initial and final correlation matrices revealed no significant change in the structure of intervariable relationships. Jennrich's test result was $\chi^2(45)=29.82$, $p=0.960$, indicating a very high similarity in the pattern of correlations before and after the study period. This suggests that the control group, which did not receive an intervention, maintained stable relationships among body composition and performance variables. The most notable individual changes occurred in correlations involving the Beep test, such as with Push-ups (+0.33), Broad jump (+0.28), and Body fat (+0.28). Despite these fluctuations, the overall matrix structure remained intact. For the experimental group, the initial-to-final comparison showed signs of reorganization, although it did not reach statistical significance. Jennrich's test yielded $\chi^2(45)=55.45$, $p=0.137$. The largest changes

occurred in key physiological relationships, especially body fat vs muscle mass (+0.41), trunk lift vs body fat (+0.41), and broad jump vs muscle mass (+0.40). These shifts point to the intervention's impact on how variables interact structurally, even if not yet confirmed statistically at the matrix level.

From final test to retention, the control group showed a statistically significant restructuring of intervariable relationships. Jennrich's test yielded $\chi^2(45)=72.61$, $p=0.0056$, confirming that the correlation structure changed meaningfully. This was especially evident in changes involving body fat, which shifted strongly in its correlation with muscle mass (+0.67), mass (+0.55), and broad jump (+0.46). In contrast, the experimental group showed no significant matrix-wide change from the final test to retention. Jennrich's test resulted in $\chi^2(45)=42.57$, $p=0.575$. Nonetheless, some moderate pair-

wise shifts were observed — particularly involving push-ups, whose correlations with the Beep test (+0.36), muscle mass (+0.35), and height (cm) (+0.34) increased.

Over the longer period from initial testing to retention, the control group experienced a clear and statistically significant alteration in its correlation structure. Jennrich's test yielded $\chi^2(45)=72.61$, $p=0.0056$ which was practically identical to the Final–Retention comparison. The strongest pairwise changes again involved body fat, especially its links to muscle mass (+0.67), broad jump (+0.53), and push-ups (+0.43). The experimental group maintained statistical stability in its intervariable relationships over the full study period. Jennrich's test yielded $\chi^2(45)=42.57$, $p=0.575$, indicating no significant deviation from the initial correlation structure. Nevertheless, notable pairwise changes included body fat (%) vs muscle

mass (+0.45), mass vs muscle mass (+0.37), and height (cm) vs Beep test (+0.36).

The results of the factor analyses calculated in the initial, final and retention measurements for the control group are presented in Table 3. Jennrich's test comparison shows no significant change in the control group's factor structure between the initial and final measurements. However, Tucker's coefficient of congruence indicates partial similarity. Notably, Initial F3 vs Final F2=0.977, and Initial F2 vs Final F3=0.954. One factor (Initial F1) showed lower similarity (~0.72), suggesting partial restructuring. Strong similarity was observed between final and retention factor structures in the control group. Final F2 vs Retention F2=0.977 and Final F3 vs Retention F3=0.955, indicating good preservation of structure.

Table 3. Factor analysis calculated for the initial, final and retention measurements for the control group (F – factor structure)

	Initial measurement				Final measurement			Retention measurement		
	F1	F2	F3	F4	F1	F2	F3	F1	F2	F3
Broad jump	-0.85	0.11	0.15	0.14	-0.77	0.31	0.27	0.83	0.18	0.06
Push-ups	-0.57	0.15	-0.49	0.25	-0.58	-0.33	0.32	0.58	0.14	-0.42
Sit-ups	-0.37	0.66	0.14	0.16	-0.56	-0.11	0.32	0.53	0.43	0.02
Trunk lift	0.10	0.14	0.00	0.88	0.05	0.44	0.51	-0.02	0.74	-0.08
Sit-reach	0.11	0.88	0.03	0.05	0.02	0.11	0.83	0.08	0.68	0.25
Beep test	-0.65	-0.23	-0.16	0.46	-0.43	0.42	-0.37	0.32	-0.48	0.38
Height	0.04	0.14	0.93	-0.04	0.19	0.85	0.13	-0.08	0.02	0.91
Mass	0.55	-0.22	0.58	0.19	0.75	0.53	0.06	-0.62	0.06	0.67
Body fat	0.94	0.01	0.17	0.11	0.93	0.12	0.09	-0.39	0.17	0.08
Muscle mass	-0.94	0.00	-0.16	-0.11	-0.93	-0.12	-0.09	0.84	-0.21	-0.25
Explained Variance	3.69	1.39	1.57	1.15	3.79	1.64	1.40	2.66	1.56	1.75
Proportion Total	0.37	0.14	0.16	0.11	0.38	0.16	0.14	0.27	0.16	0.17

The results of the factor analysis calculated for the experimental group are shown in Table 4. The factor structure remained very stable in the experimental group from the initial to final measurements. Tucker's coefficient showed initial F1 vs final F1=0.986 and F3 vs F2=0.883. Only one dimension had a weaker match, suggesting minimal structural change postintervention. Moderate-to-strong similarity was

observed in the experimental group between the initial and retention phases. F2 matched well (≈ 0.883), and F1 showed fair congruence (≈ 0.754), supporting structural consistency. Final and retention factor structures were highly congruent in the experimental group. Tucker's coefficients: F2 ≈ 0.883 and F1 ≈ 0.754 , indicating strong consistency across phases.

Table 4. Factor analysis calculated for the initial, final and retention measurements for the experimental group (F – factor structure)

	Initial measurement			Final measurement			Retention measurement	
	F1	F2	F3	F1	F2	F3	F1	F2
Broad jump	-0.38	0.37	0.63	-0.55	0.60	0.33	-0.61	0.56

(continued from previous page)

Table 3. Factor analysis calculated for the initial, final and retention measurements for the control group (F – factor structure)

	Initial measurement			Final measurement			Retention measurement	
	F1	F2	F3	F1	F2	F3	F1	F2
Push-ups	-0.46	0.06	0.68	-0.04	0.71	-0.29	-0.73	0.19
Sit-ups	0.36	0.13	0.75	-0.04	0.75	0.22	-0.28	0.73
Trunk lift	0.06	0.81	0.23	0.35	0.15	0.60	0.19	0.72
Sit-reach	0.14	0.79	0.00	0.08	0.01	0.89	0.21	0.74
Beep test	-0.28	-0.01	0.74	-0.52	0.61	0.05	-0.79	0.23
Height	0.85	0.22	0.10	0.82	0.18	0.19	0.76	0.31
Mass	0.94	0.04	-0.12	0.95	0.02	0.05	0.88	0.09
Body fat	0.76	0.01	-0.47	0.90	-0.31	0.09	0.92	0.01
Muscle mass	-0.51	-0.49	0.36	-0.92	0.26	-0.05	-0.92	0.00
Explained Variance	3.03	1.72	2.39	3.96	2.03	1.45	4.75	2.09
Proportion Total	0.30	0.17	0.24	0.40	0.20	0.14	0.48	0.21

Discussion

This study aimed to evaluate eventual qualitative changes in studied anthropometric/body composition and physical fitness indices in preadolescent children as a result of physical literacy-based education (intervention). The results indicated several important findings. First, the control group, which did not participate in physical literacy-based educational intervention, experienced certain qualitative changes, showing early signs of structural divergence. Meanwhile, factor structure and correlations among variables in the experimental group were negligible, indicating that the applied intervention supported foundations for sustainable, self-directed physical development.

Qualitative changes in the control group

As stated previously, the control group showed early signs of structural divergence. Specifically, from the initial to the final measurement, no statistically significant changes in the correlation matrix were observed, but several subtle shifts pointed to early disorganization in intervariable relationships. These changes likely reflect natural developmental variability, including growth, hormonal changes, and differences in unstructured activity levels. In explaining the background for these results, the context of the research should be briefly presented.

The study was performed during one school year, with initial testing performed in September, final testing in December, and retention testing in May. It is well known that during this period, a significant decrease in physical activity regularly occurs due to unfavorable weather conditions and

increased academic pressure (Frömel, Šafář, Jakubec, Groffik, & Žatka, 2020; Kibbe et al., 2011). Therefore, it is reasonable to expect that without the support of a specifically designed and applied structured program oriented toward increasing (or at least maintaining) the level of physical activity, internal physiological relationships may evolve inconsistently. Of particular note were shifts involving fat mass and muscular performance variables, where previously aligned patterns became weaker or more inconsistent, which almost certainly indicate fragmentation of physiological properties. It is important to note that such early signs of disintegration suggest that, even in relatively short periods, physiological systems may become less cohesive when not intentionally supported.

This trend continued and even increased in the control group during the retention phase. These dynamics were actually logical knowing the longer period between final and retention testing (five months) in comparison to the period between initial and final measurement (three months). Specifically, between the final and retention measurements, the group exhibited statistically significant changes in the correlation matrix. This clearly signals a substantial reorganization of internal relationships between anthropometric/body composition and physical fitness indices. In other words, it seems that without ongoing stimulus, previously established functional linkages between body composition and fitness began to deteriorate. The breakdown of these patterns, especially among fat mass, muscle mass, and fitness indicators, reflects a loss of physiological coordination and coherence. Such structural disorganization is not unexpected in growing children without consistent physical activity, and this is particularly possible in the winter period where previously specified fac-

tors of negative influence on physical activity are practically unavoidable (Carson & Spence, 2010).

(Lack of) qualitative changes in the experimental group

The experimental group demonstrated a markedly different pattern than the control group across all phases. First, between the initial and final measurements, no significant changes in the internal correlation structure were detected. Generally, differences between the corresponding correlation coefficients calculated for the initial and final measurements were negligible, indicating similar structures in both testing phases (e.g., September and December). Therefore, it can be said that due to exposure to a targeted PL-based intervention, the relationships among key variables remained highly stable and internally coherent. This suggests that the educational program helped to reinforce existing physiological linkages. If we consider that the 2nd study phase (from final to retention measurement) lasted longer than the previous phase (five months in comparison to three months) and that during the 2nd phase, the experimental group did not receive any intervention, it is of particular importance that in this period, structural coherence was maintained, with no evidence of regression or fragmentation. This enduring alignment among body composition and performance variables implies that the benefits of the intervention extended beyond its active duration, resulting in lasting physiological organization. These findings align with the goals of PL which emphasize autonomy, competence, and sustainable movement patterns rather than short-term gains.

Indeed, by fostering a deeper understanding of movement and encouraging consistent engagement, the PL-intervention applied here aimed to build durable motor patterns and internal motivation that support long-term physical development. In this context, the structural stability observed in our study reflects the formation of resilient, self-sustaining systems rooted in meaningful and developmentally appropriate activity. In other words, the observed “lack” of qualitative changes in the experimental group between the final and retention measurements suggests that the intervention supported the development of coordinated, transferable movement skills and physiological efficiency that remained intact even without continued instruction. Collectively, this suggests that by focusing on meaningful engagement, movement understanding, and confidence, the applied intervention may have enabled participants to internalize key aspects of physical functioning, leading to self-sustained physical adaptation. In this way, physical literacy acts not only as a pedagogical framework but also as a mechanism for stabilizing internal systems, allowing children to maintain balanced development across body composition and fitness domains.

The calculated factor analyses further support previous interpretations. In brief, the control group exhibited notable instability in factor structure across study phases, especially between the initial and retention measurements. Shifts in factor loadings and lower Tucker congruence coefficients suggest that the relationships among latent constructs became increasingly unstable without structured support. In

contrast, the experimental group displayed high factorial stability throughout. Tucker's coefficients reflected strong to near-identical alignment across all three measurement phases. This is particularly evident from the initial to final measurements. Variables related to body composition and functional performance consistently loaded on the same factors, reflecting a well-integrated and resilient internal structure. These findings illustrate that the intervention actually preserved and reinforced the latent architecture of physical development.

Final considerations

One could find surprising that the experimental group, despite participating in a structured intervention, showed relatively few changes in the internal structure of fitness and body composition variables. However, this stability of structure should not be seen as a lack of adaptation but rather as a positive indicator of functional consolidation. In a developmental stage characterized by rapid physical changes and natural variability, maintaining consistent intervariable relationships suggests that the system has adapted in a stable and organized manner. Structural stability, in this case, reflects efficiency and resilience, the body's ability to improve or maintain performance without disrupting underlying physiological mechanisms. In this context, the underlying physiological mechanisms refers to the natural and functional relationships between body composition (such as muscle mass, fat mass, and overall body size) and performance in physical fitness tasks. For example, higher skeletal muscle mass typically supports better outcomes in strength- and power-based tests such as push-ups or broad jumps, while excessive fat mass may negatively affect most of the fitness components. These relationships reflect how the body's structural components contribute to movement efficiency, force production, and energy expenditure. When these interactions remain consistent over time, the body adapts in an organized and balanced way by maintaining a logical and efficient link between body dimensions and fitness performance. Such outcomes are especially valuable in youth, where coherent development across systems is a key marker of long-term physical and functional health. Therefore, the absence of significant structural change may be interpreted not as resistance to the intervention but as a desirable outcome.

This interpretation is further supported by the nature of the applied intervention, which was grounded in the concept of PL. Rather than focusing narrowly on fitness gains, the intervention emphasized movement competence, motivation, and the understanding of physical activity as a lifelong practice. Suggested activities were designed to be developmentally appropriate, engaging, and varied while encouraging children to explore, refine, and connect movement patterns across domains. This broad and inclusive approach likely contributed to the preservation of systemic organization, helping the experimental group internalize stable relationships between body composition and performance. In line with the philosophy of PL, the observed structural consistency suggests that the intervention supported not only immediate outcomes but also the foundations for sustainable, self-directed physical development.

Limitations and strengths

This study has several limitations that should be considered. First, the assessment of physical fitness was conducted using field-based tests only. These tests are known to be practical and widely used in school settings but may lack the precision of laboratory-based measures. Second, the analysis was not stratified by gender, which may have masked sex-specific patterns in physiological development and response to the intervention. Third, the study was conducted over a relatively short duration of one academic year, which limits the ability to observe longer-term structural adaptations or delayed effects of the intervention.

Meanwhile, this is one of the rare studies to explore qualitative structural changes in fitness and body composition variables in response to a PL-based intervention, offering a novel perspective in the field. The intervention was specifically designed around physical literacy principles, ensuring developmental relevance and educational value. Furthermore, all assessments were performed using standardized protocols, with the same trained experts conducting all measurements, which enhances reliability and reduces inter-rater variability.

Conclusion

Although rarely used in sport and exercise sciences, analyses of qualitative changes offer valuable insights into how physiological systems adapt and organize over time, revealing deeper patterns of functional development. This study supports the potential of applying analyses of qualitative changes as induced by intervention protocol in physical education settings, and showed that a PL-based intervention helped maintain stable relationships between body composition and physical fitness variables. This suggests that the program supported coordinated and balanced physical development.

From a practical view, results highlight the value of using well-planned and age-appropriate activities in schools. Such programs can improve not only fitness levels but also how different physical abilities work together. Future studies should follow children for a longer time to see how stable these changes are. It would also be useful to look at differences in structural changes between boys and girls or to compare different effects among age-groups.

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Conflict of interest

The authors declare no conflicts of interest.

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Analyzing Associations Between Health Literacy, Physical Literacy, and Physical Activity: A Structural Comparison of Exercising and Non-Exercising Older Women

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Abstract

Health literacy (HL) and physical literacy (PL) are hypothesized to be important determinants of physical activity (PA) in older individuals. The aim of the study was to evidence possible associations between PL, HL, and PA, evidencing structural comparison of exercising and nonexercising postmenopausal women. The sample included 62 females (+60 years of age) divided into exercising (E; n=37) and nonexercising groups (NE; n=25). Participants were tested on HL (via the European Health Literacy Survey Questionnaire), PL (via the Perceived Physical Literacy Questionnaire), and PA (via the Nordic Physical Activity Questionnaire – short) in controlled settings. Group-specific Pearson's correlation matrices were calculated to examine associations among PL, HL, and PA. Between-group differences in correlations were tested using Fisher's z-transformation with false discovery rate correction, and structural patterns were further explored using correlation network analysis. Fisher's z tests identified significant between-group differences in selected associations, with E women showing a stronger bridging role of PL and weaker cognitive constraints on PA. Network analyses further demonstrated greater connectivity and cognitive dominance in NE women, whereas E women exhibited more differentiated and functionally organized relational structures. The results suggest that PA-related interventions targeting older women should move beyond information provision and explicitly promote PL development.

Keywords: aged women, motor skills, exercise, qualitative differences

Introduction

Maintaining functional independence is a crucial goal of healthy aging, and regular physical activity (PA) is one of its most important determinants. Specifically, regular PA has been shown to reduce the risk of cardiovascular disease in older adults and is associated with improved glycemic control and a lower incidence of type 2 diabetes (Bull et al., 2020; Colberg et al., 2016; Lear et al., 2017). Furthermore, PA has been shown to improve and preserve bone mineral density and reduce osteoporotic fracture risk in older women, and higher

levels of PA are linked with a reduced risk of sarcopenia and age-related loss of muscle function (Howe et al., 2011; Peterson, Sen, & Gordon, 2011). Last but not least, there is evidence that PA is associated with reductions in depressive symptoms in older adults (Mura & Carta, 2013). Despite all the benefits, PA levels decline with age, particularly among older women, and many do not meet recommendations of at least 150–300 minutes of moderate intensity aerobic PA per week or 75–150 minutes of vigorous intensity PA combined with resistance training two or more days per week (Sun, Norman, & While, 2013). It is generally accepted that there is a clear gap between

the known health benefits of PA and actual PA-related behavior across different age groups, which suggests that there are deeper psychosocial factors influencing engagement in PA in older age.

One determinant that could be associated with PA levels in older age is physical literacy (PL). The PL can be described as the motivation, confidence, physical competence, knowledge, and understanding to take value and responsibility for engagement in PA (Whitehead, 2010). In older adults, PL has been linked to functional movement capacity and perceived ability to perform daily physical tasks, while higher PL may also support confidence in participation in structured exercise and community-based activity programmes (Edwards, Bryant, Keegan, Morgan, & Jones, 2017). However, findings suggest that PL alone may not always be strongly correlated with PA levels in older women (Flegar et al., 2025). This implies that other factors may also be of importance.

Another possible determinant of PA in older adults is health literacy (HL). HL refers to the ability to access, understand, appraise, and apply health-related information in ways that support positive health decisions (Geets-Kesić, Maras, & Gilić, 2023; Sorensen et al., 2012). Among adults, better HL has been associated with greater participation in PA and other positive health behaviors (Van Der Heide et al., 2013). Additionally, systematic reviews indicate that inadequate HL is linked with a lower chance of engaging in PA in older populations, suggesting that individuals with higher HL are more likely to meet activity recommendations than those with limited literacy (Lim, van Schooten, Radford, & Delbaere, 2021). In studies investigating older women, higher levels of HL, including comprehension and decision making, influence engagement in PA (Babak, Majid, Rashid, Leili, & Shahryar, 2022). However, it is important to note that HL alone is not the only guarantee for consistent PA behavior in older adults. It has been shown that environmental factors, social support and health system levels all influence behavior and that HL should not be considered an isolated term (McCormack, Thomas, Lewis, & Rudd, 2017). Collectively, the current findings suggest that HL and PL can support PA engagement, but in contexts that allow individuals to use that knowledge and their abilities.

The association between HL and PL with PA is a problem worth studying, particularly in postmenopausal women. Namely, postmenopausal women experience an increased risk of cardiometabolic diseases, osteoporosis, sarcopenia, falls, and functional and cognitive decline, all of which contribute to reduced independence (Chavez, Scales, & Kling, 2021). Meanwhile, regular PA has been shown to improve bone mineral density and reduce fracture risk in postmenopausal women, particularly with resistance training (Linhares et al., 2022). In addition, exercise interventions targeting strength, balance, and coordination significantly reduce fall risk and improve neuromuscular function in older women (Bull et al., 2020). Furthermore, evidence indicates that regular PA is associated with improved mood and cognitive functioning in older women (Mura & Carta, 2013; Wang, Lii, Hsu, Ho, & Yeh, 2025). Finally, continuous engagement in PA is linked with better quality of life and prolonged independence, even

among women with preexisting chronic conditions (Chavez et al., 2021). These findings highlight the importance of identifying determinants of PA behavior, such as PL and HL, to develop effective strategies to promote active and healthy aging among older women.

From the previous literature overview, it is clear that the association between PL, HL and PA in postmenopausal women is a problem worth studying, but to the best of our knowledge, studies have rarely investigated PL and HL as simultaneous correlates of PA in postmenopausal women. In one of the rare studies, the authors recently investigated the correlations between HL and PL as predictors of PA in 60+ females and reported a significant correlation between facets of HL and PA, with no significant association between PL and PA (Flegar et al., 2025). However, this study observed a mixed sample of women and included those who were involved in recreational PA programs and those who were not included in such programs. Naturally, this specific clustering could influence the observed associations, resulting in a covariate effect of “involvement in physical exercising” (i.e., those women involved in recreational exercising logically have higher PA, irrespective of the eventual influence of HL and PL). Therefore, the aim of this study was to evaluate and compare the associations between HL, PL, and PA among postmenopausal women, emphasizing the differences in their current PA status. Specifically, we observed two subsamples: one consisted of women actively involved in recreational PA, and the age-matched subsample consisted of women who were not involved in any form of PA. To extend current knowledge, this study will not only assess correlations between PL, HL, and PA but also examine whether the structure of these relationships differs based on participation in a recreational PA program. By comparing correlation patterns across two distinct subsamples, we aim to uncover potential structural differences that may be masked in aggregated analyses. We hypothesized that the correlations would significantly differ between subsamples.

Methods

Participants

The study sample consisted of 62 women aged 60 to 80 years (71.3 ± 4.5 years) from the city of Split, located in southern Croatia. Considering the substantial influence of sociocultural factors on HL, PL, and PA, participants were recruited from a single geographical region to minimize sociocultural variability within the sample. The participants varied in health status and included individuals without major health conditions as well as those with chronic illnesses, such as diabetes, cardiovascular disease, and arthritis. All participants were physically capable of independently visiting the testing center, indicating adequate functional mobility and independence. The total sample was divided into two groups according to participants' exercise status. The first group comprised exercising participants (E; $n=37$, those who participated in regular organized physical exercise programs for more than 2 months). The second group consisted of age-matched nonexercising females (NE; $n=25$).

Participants were personally invited to take part in the

study as part of a research project conducted at the Faculty of Kinesiology, University of Split. Prior to data collection, they were informed that participation was voluntary and that they could withdraw at any time without consequence. The potential benefits and risks of participation were explained, and written informed consent was obtained from all participants.

The inclusion criteria were female sex, age 60 years or older, residence in the city of Split, sufficient functional independence to attend the testing sessions independently, and adequate cognitive capacity to understand and complete the health literacy and physical literacy questionnaires. Exclusion criteria included age below 60 years, cognitive impairment preventing questionnaire completion, and insufficient motor function or independence to attend the testing center. The study protocol was approved by the Ethics Committee of the University of Split, Faculty of Kinesiology.

Variables

Apart from age, variables in this study included PL and HL indices and PA. The PL was assessed using the Perceived Physical Literacy Questionnaire for South Eastern Europe (PPLQ-SEE) (Gilic, Sekulic, Munoz, Jaunig, & Carl, 2025). The questionnaire consists of 24 items organized into six domains: (i) physical competence, (ii) understanding, (iii) motivation, (iv) confidence, (v) knowledge, and (vi) physical activity behavior. Items within the first four domains are rated on a six-point Likert scale ranging from strongly agree to strongly disagree (5–0), whereas the PL-knowledge domain includes items with dichotomous response options (true–false). In the present study, five subdomains (PL-competence, PL-understanding, PL-motivation, PL-confidence, and PL-knowledge) along with the overall score (PL-total) were used as indicators of participants' physical literacy.

HL was measured using the validated Croatian version of the European Health Literacy Survey Questionnaire (HLS-EU-Q) (Blažević, Blazevic, & Sekulic, 2024; Geets-Kesic et al., 2023; Sestan, Zovko, & Sekulic, 2025). This instrument evaluates individuals' ability to access, understand, appraise, and apply health-related information, as well as to navigate health services and make informed health decisions. The following subscales were included in the analyses: (i) accessing healthcare-related information (HC-AC), (ii) understanding healthcare-related information (HC-U), (iii) appraising healthcare-related information (HC-AP), (iv) applying healthcare-related information (HC-APPL), (v) accessing disease prevention-related information (DP-AC), (vi) understanding disease prevention-related information (DP-U), (vii) appraising disease prevention-related information (DP-AP), (viii) applying disease prevention-related information (DP-APPL), (ix) accessing health promotion-related information (HP-

AC), (x) understanding health promotion-related information (HP-U), (xi) appraising health promotion-related information (HP-AP), and (xii) applying health promotion-related information (HP-APPL). A composite health literacy index (HL-total) was calculated using a 4-point Likert scale with response options ranging from very difficult (1) to very easy (4). Index scores were computed using the formula: $\text{index} = (\text{mean} - 1) \times (50/3)$, resulting in a standardized scale from 0 (lowest HL) to 50 (highest HL) (Sorensen et al., 2012).

PA levels were measured with the short version of the Nordic Physical Activity Questionnaire (NPAQ-short), which estimates engagement in moderate-to-vigorous (MVPA) and vigorous PA (VPA) (Danquah, Petersen, Skov, & Tolstrup, 2018). Participants reported the total time spent in PA during leisure and transportation time. Weekly minutes of MVPA and VPA were calculated.

Statistics

Participants were categorized into exercising (E) and nonexercising (NE) groups based on their current participation in organized recreational physical activity. Separate Pearson correlation matrices were computed for each group to examine bivariate associations among physical literacy (PL), health literacy (HL), and physical activity (PA) indicators.

Between-group differences in corresponding correlation coefficients were tested using Fisher's z-transformation. A total of 231 correlations were compared. To control for inflation of Type I error due to multiple testing, false discovery rate (FDR) correction was applied. Correlations remaining significant after FDR adjustment were interpreted as robust between-group differences, whereas uncorrected findings were treated as exploratory.

To further examine structural differences between groups, correlation network analyses were conducted separately for the E and NE samples. Networks were constructed using a threshold of $|r| \geq 0.30$ to retain moderate-to-strong associations. Network characteristics, including the number of edges, density, and average degree, were calculated and compared descriptively. Visual representations were generated using force-directed layouts.

All statistical analyses were performed using Statistica version 14.5 (Tibco Inc. Palo Alto, CA, USA) and Python-based analytical tools. The level of statistical significance was set at $p < 0.05$.

Results

Bivariate correlations among PL, HL, and PA indicators for the NE and E groups are presented in Tables 1 and 2, respectively.

Table 1. Pearson's correlation between study variables for the nonexercising group (coefficients > 0.38 are significant at p < 0.05)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
PL-competence (1)	-																			
PL-understanding (2)	-0.07	-																		
PL-motivation (3)	-0.08	-0.03	-																	
PL-confidence (4)	0.09	0.05	0.10	-																
PL-knowledge (5)	-0.30	0.17	0.05	0.48	-															
PL-total (6)	0.26	0.16	0.55	0.80	0.52	-														
HC-AC (7)	0.13	0.38	0.06	-0.15	0.11	0.07	-													
HC-U (8)	0.01	0.51	0.04	-0.05	0.25	0.14	0.88	-												
HC-AP (9)	-0.04	0.62	-0.20	-0.04	0.08	-0.04	0.74	0.77	-											
HC-APPL (10)	0.26	0.55	0.00	0.06	-0.06	0.17	0.80	0.82	0.78	-										
DP-AC (11)	-0.05	0.43	-0.23	-0.22	0.03	-0.20	0.80	0.72	0.80	0.76	-									
DP-U (12)	0.11	0.63	-0.24	0.13	0.22	0.13	0.76	0.83	0.73	0.86	0.78	-								
DP-AP (13)	-0.07	0.71	-0.02	0.17	0.19	0.20	0.71	0.70	0.78	0.79	0.79	0.86	-							
DP-APPL (14)	-0.37	0.39	-0.36	-0.09	0.09	-0.29	0.50	0.39	0.70	0.43	0.76	0.53	0.67	-						
HP-AC (15)	-0.13	0.65	-0.10	-0.14	0.06	-0.08	0.61	0.57	0.67	0.68	0.71	0.72	0.76	0.58	-					
HP-U (16)	-0.23	0.37	-0.35	-0.32	-0.06	-0.41	0.63	0.50	0.70	0.52	0.76	0.56	0.59	0.82	0.81	-				
HP-AP (17)	0.09	0.51	-0.06	-0.19	0.06	-0.03	0.82	0.83	0.66	0.78	0.79	0.84	0.71	0.48	0.80	0.73	-			
HP-APPL (18)	0.24	0.45	-0.04	-0.46	-0.42	-0.27	0.43	0.27	0.53	0.42	0.52	0.33	0.41	0.33	0.45	0.38	0.38	-		
HL-total (19)	-0.03	0.62	-0.16	-0.15	0.05	-0.08	0.87	0.82	0.89	0.85	0.93	0.87	0.88	0.74	0.85	0.82	0.88	0.55	-	
MOD-VIG PA (20)	0.10	-0.15	0.39	0.49	0.17	0.54	-0.17	-0.19	-0.37	-0.20	-0.46	-0.18	-0.14	-0.54	-0.38	-0.62	-0.40	-0.17	-0.40	-
VIG PA (21)	-0.04	-0.35	-0.08	-0.32	-0.27	-0.36	0.09	0.00	-0.25	-0.12	-0.04	-0.11	-0.17	0.07	-0.18	0.08	0.05	-0.31	-0.09	-0.32

PL – physical literacy, HC-AC – accessing healthcare-related information, HC-U – understanding healthcare-related information, HC-AP – appraising healthcare-related information, HC-APPL – applying healthcare-related information, DP-AC – accessing information related to disease prevention, DP-U – understanding information related to disease prevention, DP-AP – appraising information related to disease prevention, HP-APPL – applying information related to disease prevention, HP-AC – accessing information related to health promotion, HP-AP – appraising information related to health promotion, HP-U – understanding information related to health promotion, HP-APPL – applying information related to health promotion, MOD-VIG PA – moderate to vigorous physical activity, VIG PA – vigorous physical activity.

Table 2. Pearson's correlation between study variables for the exercising group (coefficients >0.33 are significant at p < 0.05)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
PL-competence (1)	-																			
PL-understanding (2)	-0.09	-																		
PL-motivation (3)	0.10	0.26	-																	
PL-confidence (4)	-0.14	0.18	0.01	-																
PL-knowledge (5)	-0.20	0.14	-0.21	0.31	-															
PL-total (6)	0.56	0.32	0.30	0.57	0.42	-														
HC-AC (7)	-0.06	0.41	0.19	0.23	0.01	0.19	-													
HC-U (8)	0.14	0.11	0.22	0.20	-0.30	0.14	0.35	-												
HC-AP (9)	0.13	0.25	0.14	0.35	-0.06	0.32	0.45	0.56	-											
HC-APPL (10)	-0.04	0.05	0.22	0.21	-0.11	0.10	0.44	0.72	0.63	-										
DP-AC (11)	0.15	0.32	0.22	0.24	0.03	0.35	0.64	0.40	0.74	0.55	-									
DP-U (12)	-0.05	0.27	0.24	0.25	0.12	0.25	0.23	0.49	0.51	0.69	0.50	-								
DP-AP (13)	0.03	0.32	0.06	0.33	-0.04	0.23	0.38	0.46	0.70	0.50	0.56	0.54	-							
DP-APPL (14)	-0.05	0.17	0.20	0.29	-0.11	0.14	0.04	0.38	0.31	0.30	0.20	0.26	0.49	-						
HP-AC (15)	0.08	0.21	0.03	0.29	-0.04	0.22	0.51	0.32	0.64	0.42	0.64	0.33	0.71	0.34	-					
HP-U (16)	0.04	0.26	0.04	0.08	-0.07	0.09	0.32	0.45	0.59	0.54	0.58	0.53	0.69	0.43	0.66	-				
HP-AP (17)	0.06	0.24	0.22	0.24	-0.18	0.18	0.48	0.35	0.54	0.51	0.62	0.58	0.53	0.25	0.44	0.53	-			
HP-APPL (18)	-0.07	0.15	0.14	0.45	-0.08	0.21	0.22	0.46	0.54	0.56	0.38	0.71	0.72	0.43	0.48	0.44	0.56	-		
HL-total (19)	0.05	0.32	0.20	0.36	-0.09	0.28	0.60	0.67	0.83	0.76	0.79	0.69	0.85	0.50	0.79	0.79	0.71	0.72	-	
MOD-VIG PA (20)	0.13	-0.06	-0.06	-0.04	-0.06	0.02	-0.04	-0.18	-0.16	-0.28	-0.09	-0.25	-0.16	-0.12	-0.04	-0.20	-0.09	-0.28	-0.21	-
VIG PA (21)	0.25	0.10	0.07	0.21	-0.09	0.27	0.13	0.16	0.36	0.16	0.30	0.23	0.49	0.37	0.40	0.38	0.35	0.37	0.43	-0.11

PL – physical literacy, HC-AC – accessing healthcare-related information, HC-U – understanding healthcare-related information, HC-AP – appraising healthcare-related information, HC-APPL – applying healthcare-related information, DP-AC – accessing information related to disease prevention, DP-U – understanding information related to disease prevention, DP-AP – appraising information related to disease prevention, DP-APPL – applying information related to disease prevention, HP-AC – accessing information related to health promotion, HP-U – appraising information related to health promotion, HP-AP – applying information related to health promotion, HP-APPL – applying information related to health promotion, MOD-VIG PA – moderate to vigorous physical activity, VIG PA – vigorous physical activity.

In the NE group, correlations were generally stronger and more homogeneous, particularly among HL subscales, which demonstrated high intercorrelations. Several PL domains also exhibited moderate-to-strong associations with PA indicators. In contrast, the E group displayed a more differentiated correlation pattern. Intercorrelations among HL subscales were generally weaker, and relationships between PL domains

and PA indicators were less uniform. Visual inspection of the matrices suggested greater functional specialization among constructs in physically active women compared with their inactive counterparts.

To formally examine differences between corresponding correlation coefficients in the NE and E groups, Fisher's z tests were applied, and the results are briefly reported in Table 3.

Table 3. Significant between-group differences in correlation coefficients between control and experimental groups based on Fisher's z-tests with FDR correction

Variable 1	Variable 2	Pearson's r (Non-Exercising)	Pearson's r (Exercising)	Z	p	FDR p
HC-AC	HC-U	0.88	0.35	3.72	<0.001	0.041
PL-confidence	HP-APPL	-0.46	0.45	-3.63	<0.001	0.03

In general, a total of 231 correlations were compared. To control for multiple testing, false discovery rate (FDR) correction was applied. After FDR adjustment, two correlations differed significantly between groups. The association between the HC-AC and HC-U subscales was significantly stronger in the NE group than in the E group ($Z=3.72$, $p<0.001$, $FDR\ p=0.041$). Conversely, the relationship between the PL-confidence and the HP-APPL was significantly stronger in the E group ($Z=-3.63$, $p<0.001$, $FDR\ p=0.030$). In addition to these

robust effects, several further correlations demonstrated notable between-group differences prior to correction, particularly those involving HL and PA indicators, as well as PL domains and moderate-to-vigorous PA.

To explore higher-order structural properties of the relationships among PL, HL, and PA, correlation networks were constructed separately for each group using a threshold of $|r|\geq 0.30$. The resulting networks are presented in Figure 1.

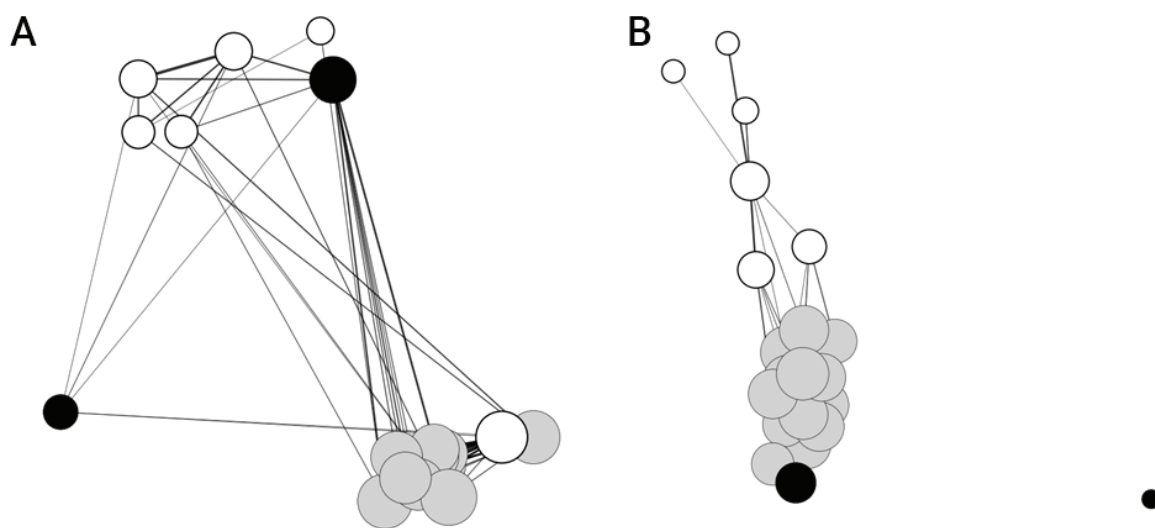


Figure 1. Network graphs of variable associations in nonexercising (1A) and exercising (1B) group (grey circles - physical literacy variables, white circles – health literacy variables, black circles – physical activity variables)

The NE group network (Figure 1A) consisted of 21 nodes and 117 edges, with a network density of 0.56 and an average degree of 11.14. This network was characterized by high connectivity and strong clustering among HL subscales, indicating substantial interdependence between health-related competencies. Several PL domains and PA indicators were embedded within this dense structure. The E group network (Figure 1B) comprised 21 nodes and 96 edges, with a density of 0.46 and an average degree of 9.14. Compared with the NE

group, this network exhibited lower connectivity and greater modularity. HL subscales formed a coherent core cluster, while the PL-total score occupied a more central bridging position between (both) literacy-related domains and PA. Moderate-to-vigorous physical activity showed weaker integration within the network structure. Overall, these network characteristics suggest that participation in recreational physical activity is associated with a more differentiated and less saturated relational structure among the PL, HL, and PA constructs.

Discussion

There are several important findings of this study. First, in the NE group, HL-facets formed a highly interconnected and homogeneous system, characterized by (i) strong coupling among HL variables and (ii) substantial dependence of PA on HL-competencies. On the other hand, the E group demonstrated greater functional differentiation in HL dimensions (evident as weaker interdependence among HL components) and a more prominent integrative role of PL. Therefore, our initial study hypothesis can be accepted.

Interconnection between health literacy facets in nonexercising and exercising groups

One of the most important findings of this study is the evidently stronger interconnection among HL subscales in the NE group, particularly between the HL-assessing and HL-understanding dimensions. This pattern suggests that, in inactive women, health-related skills tend to function as a tightly integrated cognitive system. Interestingly, although investigations consistently reported strong correlations between HL-facets and health outcomes, studies rarely examined the correlations between HL-facets in older populations (Fry et al., 2024). However, it is reasonable to suggest that the integration in HL subdomains we have found herein in nonexercising women may reflect a high level of health awareness. On the other hand, it may also indicate limited flexibility in applying health knowledge to everyday behavior, including participation in PA.

More specifically, inactive women may rely predominantly on careful deliberation and risk evaluation when making health-related decisions. As a matter of fact, such a mechanism is not known, and studies repeatedly emphasize that thorough risk evaluation is essential for sound health-related decision-making, being a component of effective health decision-making (Desmond, Brubaker, & Ellner, 2013). However, it is not hard to suppose that such cognitive (over)dominance may lead to cautious or avoidant attitudes toward PA. While such caution may appear reasonable, frequent focus on potential risks, physical limitations, or negative health outcomes may narrow the perspective on positive outcomes of regular PA. In other words, individuals may overlook the positive effects of physical exercise, even when those benefits are well known and clearly understood. As a result, women may delay initiating exercise, participate less frequently, or discontinue activity altogether, despite having sufficient health-related knowledge and understanding of the benefits of PA.

In contrast, the E group demonstrated weaker interconnections among HL subdomains, indicating greater differentiation of health-related skills. Quite opposite to nonactive participants, this pattern may suggest a more adaptive and context-sensitive use of health information. In other words, in this group of participants, specific HL competencies are likely to be applied according to situational demands. For example, when “understanding” is needed, individuals will adequately comprehend health-related information. Additionally, when “action” is needed, they will be more likely to act in ways that promote health (including regular exercising). In other words,

we may suppose that participation in structured PA programs may contribute to the development of more functional and flexible HL profiles.

Health literacy as a correlate of physical activity in inactive women

In the NE group, HL facets were not only strongly interconnected but were also closely linked to PA indicators. In general, the positive association between HL and PA is a known issue, and similar results have already been reported in the literature (Buja et al., 2020; Lim, van Schooten, Radford, & Delbaere, 2021). This structure suggests that behavioral engagement in inactive women may be strongly regulated by cognitive evaluations, health concerns, and perceived risks. Such reliance on cognitive regulation may foster conservative or avoidant behavioral patterns. This is particularly possible among older women with chronic health conditions and those who fear injury or are uncertain regarding exercise safety. Specifically, when health-related thinking is not supported by positive practical experience, it may discourage regular PA. For example, a woman with joint pain may carefully analyze the potential risks of exercise and decide to avoid walking or group exercise classes, even though moderate physical activity could be beneficial for her health (Law, Markland, Jones, Maddison, & Thom, 2013). In this context, HL (rather than facilitating action) may unintentionally reinforce inactivity through heightened risk sensitivity.

In contrast, in the E group, associations between HL facets and PA indicators were weaker, suggesting that PA engagement in this group was less directly constrained by cognitive evaluation alone. This weaker link may indicate that careful health-related thinking plays a smaller role in guiding PA behavior among physically active women. The background mechanism of such (lack) of association in this particular group of participants is logical and understandable. For example, women who regularly participate in exercise programs may decide to attend training sessions or go for walks based on habit, enjoyment, or social interaction rather than continuous evaluation of potential health risks and benefits. Similarly, instead of repeatedly considering whether exercise is safe or appropriate, physically active women may rely on their previous positive experiences, established routines, and confidence in their abilities when deciding to remain active. The presented mechanism has already been confirmed, particularly in older adults, and studies repeatedly reported that enjoyment and social interaction (rather than health risk-benefit evaluation) drive exercise participation at later ages (Franco et al., 2015). On the other hand, such “chain reactions” are hardly expectable in women who do not regularly exercise.

Physical literacy as a bridge between health literacy and physical activity in the exercising group

Our results highlight the central role of PL in physically active women. Specifically, network and correlation analyses identified PL (particularly the PL total score) as a key “bridge” between HL and PA in the E group. Moreover, the positive

association between PL confidence and HL application was significantly stronger among active participants, whereas this relationship was weaker in the NE group. These findings suggest that PL may serve as a critical mechanism facilitating the translation of cognitive resources derived from HL facets into sustained PA behavior among women who are already physically active. Simply theoretically, this interpretation is in line with Whitehead's conceptualization of PL, which emphasizes "the integration of motivation, confidence, physical competence, knowledge, and understanding in supporting lifelong engagement in physical activity" (Whitehead, 2010). Within this framework, physically literate individuals are better equipped to apply health-related knowledge in meaningful and context-appropriate ways.

In other words, we may suppose that active participation in recreational programs may reduce cognitive constraints by providing repeated positive experiences that reinforce perceived competence and confidence. Women who regularly attend supervised exercise may experience reduced pain, improved mobility, and enhanced mood. It altogether can gradually replace risk-focused evaluations with embodied confidence. Over time, physical activity may become less influenced by careful health-related concerns. Instead, it may be guided more by perceived competence, enjoyment, and established routines, which support sustained engagement. Supportively, studies highlighted that repeated mastery experiences and positive affective responses (achieved by participation in physical activity) may strengthen motivational processes linked to long-term PA in older adults (McAuley, Jerome, Elavsky, Marquez, & Ramsey, 2003; Teixeira, Carraça, Markland, Silva, & Ryan, 2012). Although the precise mechanisms underlying these effects cannot be definitively established within the present study, this pattern of findings may help explain the observed differences in correlations between active and inactive participants.

Meanwhile, in inactive women, PA appeared to depend more strongly on individual competencies. In this group, PL confidence most likely did not translate effectively into PA as a health-promoting action. This pattern may reflect already mentioned motivational barriers such as low exercise self-efficacy, fear of injury, perceived physical limitations, or insufficient behavioral opportunities in the absence of organized programs. Indeed, even when individuals perceive themselves as capable, concerns about pain, fatigue, social evaluation, or previous negative exercise experiences may reduce their willingness to initiate or maintain regular PA (Bandura, 1997).

Limitations and strengths

Before reaching conclusions, several limitations should be acknowledged. First, the cross-sectional design precludes causal inference regarding the direction of the observed relationships. Therefore, longitudinal and experimental studies are needed to determine whether participation in physical activity leads to structural reorganization among physical literacy, health literacy, and physical activity or whether preexisting relational patterns influence program adherence. Second, the relatively small sample size limits statistical power and the generalizability of the findings. In addition, participants were recruited from a single

geographical region characterized by a Mediterranean climate and specific sociocultural and environmental conditions that may facilitate or constrain physical activity engagement. Therefore, the present results may not be fully generalizable to older women living in different climatic, cultural, or infrastructural contexts. Third, the reliance on self-report measures may have introduced response and recall biases. Future research should incorporate objective assessments of physical activity and performance-based measures of physical and health literacy to enhance measurement precision.

On the other hand, this study is among the first to examine structural differences in the associations between HL, PL, and PA separately in exercising and nonexercising participants. Furthermore, the focus on postmenopausal women, a population with specific health needs and well-documented benefits from regular PA, represents a significant strength of the present study.

Conclusion

The presented results highlight PL as a key mechanism through which health-related knowledge and understanding are translated into sustained PA in older women. In physically active women, confidence, competence, and embodied experience (as evidenced by higher levels of PL) appear to facilitate the practical application of health information, thereby supporting more autonomous and self-regulated behavior.

From an applied perspective, these results suggest that interventions targeting older women should move beyond information provision and explicitly promote PL development. Programs that emphasize skill acquisition, confidence building, and positive movement experiences may be particularly effective in fostering long-term engagement in physical exercise programs.

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Conflict of interest

The authors declare no conflicts of interest.

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Wearable-Monitored External Workload (GPS/GNSS/IMU) and Lower-Limb Muscle Injuries in Football: A Systematic Review and Exploratory Data Synthesis

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Abstract

Lower-limb muscle injuries are common in football and are often linked to fluctuations in training load. Global Positioning System/Global Navigation Satellite System (GPS/GNSS) and Inertial Measurement Unit (IMU) based monitoring of external workload is now routine, yet evidence for its association with injury risk remains inconsistent. This review aimed to synthesize current evidence on the relationship between GPS/IMU-derived workload variables and lower-limb muscle injuries in football players. Following PRISMA guidelines, we searched PubMed and Scopus to September 2025. Eligible studies involved football players at any competitive level, reported GPS/IMU-based workload metrics, and included muscle-injury outcomes. Study quality was assessed with the Newcastle–Ottawa Scale. Twelve studies met the inclusion criteria for qualitative synthesis; however, only four studies provided extractable statistical data for quantitative pooling. These four studies contributed 21 independent effect-size comparisons, analysed as odds ratios (ORs) or relative risks (RRs). Workload definitions and thresholds varied substantially across studies—particularly speed zones, sprint metrics, and ACWR calculations—limiting direct comparability. The exploratory quantitative analysis of OR-based studies showed no significant association between high workload and injury risk (pooled OR=1.33, 95% CI 0.85–2.07; $p=0.21$; $I^2=93\%$). In contrast, the RR-based analysis indicated a significant association, with high workloads more than doubling injury risk (pooled RR=2.33, 95% CI 1.65–3.30; $p<0.00001$; $I^2=0\%$). Given the small number of extractable studies and substantial heterogeneity in workload definitions, these findings should be interpreted as exploratory rather than confirmatory. GPS/IMU-monitored external workload may be associated with muscle-injury risk, but the direction and magnitude depend on analytic approach and how “high workload” is operationalized. Larger, multi-club prospective studies with standardized workload definitions are needed to strengthen the evidence base.

Keywords: external workload, football, GPS monitoring, IMU monitoring, muscle injury, systematic review, meta-analysis

Introduction

Lower-limb muscle injuries are among the most prevalent health problems in football (soccer) (Ferdinand et al., 2025; Nilsson et al., 2023; Nobari et al., 2021, 2022). They reduce on-field performance and cause short- and long-term absences, which affects team continuity and results (Fanchini et al., 2018; Windt et al., 2018). The high incidence of muscle injuries makes this issue a significant concern in sports medicine and athlete performance management.

One factor believed to contribute to injuries is training load. The physical load from training and competition, referred to as training load, is defined as ‘the cumulative stress placed on an individual from multiple training sessions and matches over a given period of time’ (Zumeta-Olaskoaga et al., 2025). Training load is generally a result of training intensity and duration, and research shows that an increase in training load is associated with an increase in the frequency and severity of injuries (Georgiadis et al., 2024; Sumartiningsih et al., 2022). Excessive, disproportionate, or poorly managed training load can increase the risk of lower-limb muscle injuries (Carling et al., 2018; Windt et al., 2017; Windt & Gabbett, 2017). Therefore, monitoring and managing training load is crucial in preventing injuries and optimizing player performance.

Recent technological advances have enabled routine monitoring of athlete-performance indicators. In professional football, Local Positioning Systems (LPS), GNSS/ GPS) and IMU are used to quantify external load. LPS and GPS are used to measure distance traveled at various speed zones (e.g. high-speed running distance or HSRD), or the number of speed changes, (e.g. acceleration (ACC). Meanwhile, IMUs capture movement dynamics and estimate the mechanical load imposed during training and matches. These systems are now standard for real-time external-load monitoring and support day-to-day training decisions (Colby et al., 2014; de Dios-Álvarez et al., 2023; Piłka et al., 2023; Saberisani et al., 2025). The data collected includes distance, speed, sprints, acceleration-deceleration, and power output.

In practice, several key variables are used to evaluate external load, including total distance, high-speed running, sprint distance, number of accelerations-decelerations, and the acute: chronic workload ratio (ACWR) (Buchheit et al., 2021; Clemente et al., 2021; Colby et al., 2014; Fousekis et al., 2025; Georgiadis et al., 2024). These variables characterize the intensity and distribution of training load, which may be associated with injury risk.

However, the operational definitions of these workload metrics vary widely across studies (Buchheit et al., 2021; Windt et al., 2018; Windt & Gabbett, 2017). Speed thresholds for high-speed running and sprinting differ considerably between teams and tracking systems, and ACWR is calculated using multiple non-equivalent formulas. Similarly, accelerations, decelerations, and sprint variables are inconsistently defined across the literature (Buchheit et al., 2021; Windt et al., 2018; Windt & Gabbett, 2017). This lack of standardization has created substantial heterogeneity in how “training load” is conceptualized and measured, contributing to inconsistent findings regarding its association with injury risk.

However, no systematic review or meta-analysis has

specifically focused on the association between GPS/GNSS/IMU-derived exercise load variables and lower-limb muscle injuries in football players. This gap is significant because, although monitoring technology is now standard in professional practice, the scientific evidence supporting its use in injury prevention remains limited and fragmented. This study aims to systematically synthesize observational findings on the relationship between GPS-based training load variables and the risk of lower-limb muscle injuries in football players. The results are expected to provide a more comprehensive scientific understanding and offer practical insights for coaches, medical staff, and performance managers in developing injury prevention strategies informed by training load monitoring technologies.

Given the substantial variability in workload definitions and analytic approaches across studies, a systematic synthesis is needed to clarify the current evidence and assess the extent to which meaningful conclusions can be drawn.

Methods

Search strategy

A comprehensive literature search was performed in Scopus and PubMed databases to identify relevant studies examining the association between GPS-monitored workload and lower-limb muscle injuries in football players. The search performed up to September 4, 2025, included no restrictions on publication year, using a combination of controlled vocabulary and free-text terms. Search terms covered sport-related keywords (“soccer,” “football”), monitoring technologies (“GPS,” “GNSS,” “local positioning system,” “wearable tracking”), workload variables (“training load,” “external load,” “acute: chronic workload ratio,” “high-speed running,” “sprint distance,” “acceleration,” “deceleration,” “distance covered”), and injury outcomes (“muscle injury,” “hamstring injury,” “quadriceps injury,” “adductor injury,” “calf injury,” “lower-limb injury,” “time-loss injury,” “injury incidence,” “injury risk,” “injury occurrence”). Eligible study designs were cohort, longitudinal, prospective, observational, and randomized controlled trials. Only peer-reviewed, English-language articles indexed in PubMed and Scopus were eligible. The reference lists of included studies were also screened to identify additional relevant publications not retrieved by the database search.

Study selection and eligibility criteria

The initial search yielded 100 records (Scopus =70; PubMed =30). After removing duplicates, 70 unique articles were screened by title and abstract. Of these, 33 were excluded for not meeting the inclusion criteria (e.g., irrelevant population, GPS not used for workload monitoring, or outcomes unrelated to injury). The full text of 37 articles was assessed for eligibility, and 25 studies were excluded for the following reasons: no GPS workload data (n=9), no injury outcomes reported (n=5), or inappropriate study design (not RCT, cohort, case-control, or longitudinal observational; n=11). Ultimately, 12 articles fulfilled all eligibility criteria and were included in the qualitative synthesis. Of these, four provided sufficient statistical information for quantitative synthesis. Because several studies reported multiple effect sizes (e.g., Malone et

al., 2018: six outcomes; Jaspers et al., 2018: nine outcomes; Nobari et al., 2021: four outcomes; Nobari et al., 2022: two outcomes), the meta-analysis included a total of 21 independent comparisons (15 OR-based and 6 RR-based), which were analysed according to their reported effect measure. The review followed PRISMA guidelines for systematic reviews and meta-analyses, and the protocol was prospectively registered with PROSPERO (CRD420251146818). The PRISMA flow diagram (Figure 1) summarizes the study selection process. When critical statistical information was unavailable, corresponding authors were contacted (up to three times) to request additional data. Studies that remained incomplete were excluded from the quantitative synthesis but were described narratively. The eligibility criteria were defined using the PICOS framework. The population (P) included male and female football players of all competitive levels (professional, semi-professional, academy, and youth). The exposure (I)

was workload variables measured with GPS/IMU technology, including total distance, high-speed running distance, sprint distance, accelerations/decelerations, ACWR, and player load. The comparators (C) included injured versus non-injured players, or groups exposed to different workload levels (e.g., high vs. low workload). The outcomes (O) were lower-limb muscle injuries (hamstring, quadriceps, adductor, calf), measured by incidence, recurrence, and time-loss injuries. Eligible study designs (S) were primary studies such as randomized controlled trials (RCTs), cohort, case-control, and longitudinal observational studies.

Although twelve studies met the eligibility criteria and were included in the qualitative synthesis, only four studies provided extractable numerical data (i.e., odds ratios, relative risks, or raw injury counts) suitable for quantitative pooling. The remaining studies lacked compatible effect estimates or reported workload variables using non-comparable formats.

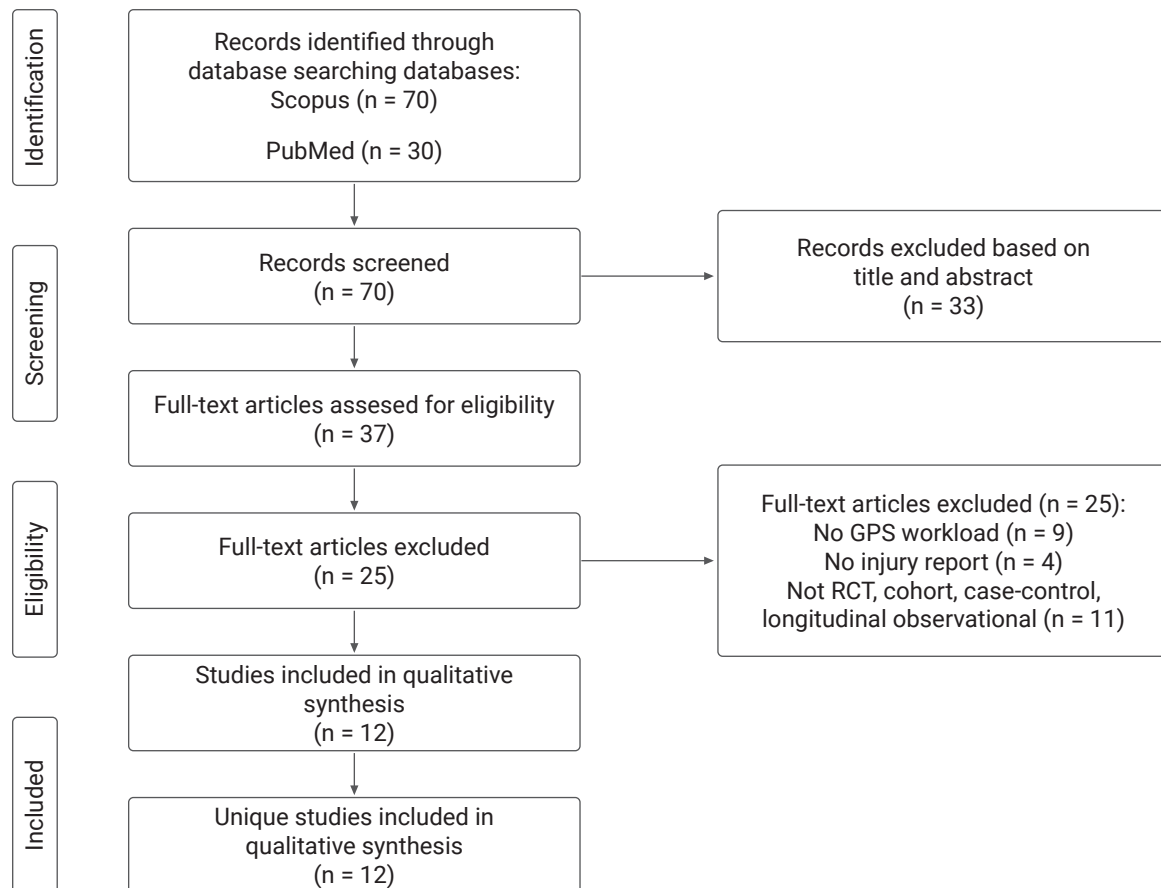


Figure 1. Flowchart of study selection

Definition and categorization of workload variables

Workload variables reported across the included studies were highly heterogeneous in definition, thresholding, and calculation methods. To enable transparent synthesis, we grouped workload metrics into broader conceptual categories based on their physiological and mechanical characteristics. Total distance, high-speed running distance, and sprint distance were classified as “locomotor distance-based metrics.”

Accelerations, decelerations, and change-of-direction actions were categorized as “accelerometry-based metrics.” Acute/chronic workload ratio (ACWR) variables were grouped separately because of their distinct temporal structure and the use of multiple non-equivalent calculation methods (e.g., rolling average vs. EWMA-based models). These categorizations were used to guide narrative comparison and to avoid pooling conceptually incompatible variables within the meta-analysis.

Study characteristics

Two researchers (YNH and SS) independently extracted data using a predefined form. Variables collected included: study characteristics, population type, GPS/IMU technology, injury definition, sample size, and effect-size values (OR, RR, HR) with 95% CI or raw data. Disagreements were resolved through discussion, and a third reviewer (SR) was consulted when necessary. Inter-rater reliability was calculated (Cohen's κ /ICC). For the NOS quality assessment, inter-rater reliability was good (ICC=0.84, 95% CI).

Methodological quality assessment

Two authors independently assessed the methodological quality of the included studies using criteria adapted from the Newcastle–Ottawa Scale (NOS) for cohort and observational designs. The assessment focused on three domains: (1) selection of participants and exposure measurement (e.g., clarity of the football population, validity of GPS devices); (2) comparability of groups (e.g., adjustment for potential confounders such as age, playing position, or match exposure); and (3) outcome assessment (e.g., definition of muscle injury, objective confirmation, and adequacy of follow-up). Each study received a risk-of-bias rating (low, moderate, or high). Disagreements were resolved through discussion until consensus was reached. The NOS was chosen because most included studies used observational cohort designs, and the criteria were adapted to the context of sports injuries. Figure 1 shows the PRISMA flow diagram for study selection.

Most studies were rated as having moderate methodological quality, mainly due to limited sample sizes, single-team designs, and lack of adjustment for confounding variables. Nevertheless, all included articles employed prospective or longitudinal injury surveillance and used validated GPS or GNSS devices, supporting the reliability of workload and injury measurements. Any discrepancies in quality ratings between reviewers were resolved through discussion until consensus was reached.

Most studies were rated as of moderate quality, primarily due to small sample sizes, single-team designs, and limited adjustment for potential confounders. Nevertheless, using validated GPS/GNSS devices and standardized injury definitions strengthened the methodological rigor across studies. Inter-rater reliability of NOS ratings was good (ICC=0.84, 95% CI).

Study outcomes and effect size calculation

The primary outcome was the incidence of lower-limb muscle injuries in football players, including hamstring, quadriceps, adductor, and calf injuries, as well as composite categories of non-contact and overuse muscle injuries. Only studies reporting outcomes according to established consensus definitions (e.g., time-loss or medical-attention criteria) were included. Exposure variables comprised training-load metrics obtained from GPS/GNSS and IMU devices, including total distance, high-speed running distance, sprint distance, accelerations and decelerations, weekly acute workload, four-week rolling-average chronic workload, ACWR, and composite in-

dices such as player load.

For the meta-analysis, studies were eligible if they provided sufficient statistical information (odds ratios [ORs], relative risks [RRs], hazard ratios [HRs]), or raw data permitting conversion to effect sizes). Reported ORs and RRs were extracted directly, and when 95% confidence intervals (CIs) were available, log odds ratios (logOR) and their standard errors (SE) were computed using standard formulas. If only HRs were reported, they were synthesized qualitatively but not pooled. Log odds ratios were calculated as $\log\text{OR} = \ln(\text{OR})$, while the standard error was derived from the 95% CI using the formula $\text{SE}_{\log\text{OR}} = (\ln[\text{upper_CI}] - \ln[\text{lower_CI}]) / (2 \times 1.96)$, and the variance as $\text{vi} = \text{SE}_{\log\text{OR}}^2$ (\ln denotes the natural logarithm).

Effect sizes were pooled using a random-effects model to account for between-study heterogeneity. Subgroup analyses were planned to compare non-contact and overuse injuries; however, because of the limited number of studies, these comparisons were interpreted narratively rather than pooled. Heterogeneity was assessed using Cochran's Q (Chi^2), τ^2 , and I^2 , and publication bias was assessed visually using funnel plots. The quantitative synthesis was performed in Review Manager (RevMan, version 5.4; Cochrane Collaboration, London, UK). RevMan generated forest plots displaying individual study estimates ($\log(\text{OR})$ or $\log(\text{RR})$), their standard errors and study weights, alongside the pooled effect size with 95% CI, illustrating consistency across studies. Heterogeneity statistics (τ^2 , Chi^2 , and I^2) and the overall test of effect (Z statistic and p -value) were also produced. In accordance with PRISMA guidelines, the forest plots were exported directly from RevMan and incorporated into the Results section.

Because the number of eligible studies was extremely limited ($n=4$), subgroup analysis and meta-regression could not be performed due to insufficient statistical power. Although 15 odds-ratio comparisons were analyzed, these outcomes originated from only two original studies, which further restricted the ability to explore sources of heterogeneity. Consequently, while several training-load indicators suggested an elevated injury risk, the high heterogeneity ($\tau^2=0.69$, $\text{Chi}^2=192.56$, $p<0.00001$, $I^2=93\%$) could not be meaningfully investigated, and a random-effects model was applied for all pooled estimates.

Secondary analysis

Secondary analyses were performed to evaluate the robustness of the pooled effects. Publication bias was assessed visually using funnel plots; however, because fewer than ten studies were included in the meta-analysis, the interpretation of any asymmetry was limited. Sensitivity analyses (e.g., leave-one-out procedures) and formal statistical tests (e.g., Egger's regression test, prediction intervals) were initially planned but not performed due to the small number of eligible studies. Therefore, the results of the secondary analyses should be interpreted with caution. All analyses used Review Manager (RevMan, version 5.4; Cochrane Collaboration, London, UK).

Because the included studies reported effect estimates using different statistical measures (i.e., odds ratios and relative risks), pooling was performed separately for OR-based

and RR-based outcomes. Converting OR to RR was avoided because the required baseline-risk assumptions could not be satisfied given the heterogeneity across studies. Therefore, two independent meta-analyses were conducted, and their findings were interpreted with caution due to the limited number of available studies. Because the number of included studies was limited (n=4), subgroup analysis and meta-regression could not be performed due to insufficient statistical power. Consequently, heterogeneity was addressed using a random-effects model for all meta-analytic calculations.

Results

The initial database search identified 100 records (Scopus, n=70; PubMed, n=30). After deduplication, 70 unique records remained for screening. Following title and abstract screening, 33 records were excluded, leaving 37 full-text articles for eligibility assessment. Of these, 25 were excluded due

to lack of GPS/GNSS-derived workload data (n=9), absence of injury outcomes (n=5), or ineligible study design (n=11). Consequently, 12 studies met all inclusion criteria and were included in the qualitative synthesis and methodological quality assessment (Figure 1). Because several studies reported multiple effect sizes (e.g., Malone et al., 2018: six; Jaspers et al., 2018: nine; Nobari et al., 2021: four; Nobari et al., 2022: two), the meta-analysis was based on 21 independent comparisons (15 OR-based, 6 RR-based). The studies varied in sample size, competitive level, and exposure measures, but all met the eligibility criteria and provided sufficient statistical information for pooling. The methodological quality of these 12 studies was appraised using the Newcastle–Ottawa Scale (NOS). Overall, the studies demonstrated acceptable quality, with scores ranging from 5 to 8. Based on the ratings, five studies were categorized as low risk of bias, six as moderate, and one as high. Details of the assessment are presented in Table 2.

Table 1. Study characteristics

Authors (Year)	Country	Population	Load Variables	Injury Outcomes	Key Results	Meta-analysis Eligibility
Morgans et al. (2025)	England	30 EPL players	Sprint distance	Hamstring injury	Players who sustained injuries had higher sprint distance in the week prior to injury (p = 0.038).	Insufficient data
Zumeta-Olaskoaga et al. (2025)	Spain	36 LaLiga players	Cumulative distance, avg. speed	Non-contact injuries	Cumulative workload from the last seven sessions was associated with increased injury risk.	Not compatible
Soler et al. (2025)	Spain	41 LaLiga players	TD, HMLD, Acc/Dec	Calf injuries	Greater total distance and high metabolic load distance in the week before injury were significantly associated with calf injuries.	Not compatible
Marshall et al. (2024)	Germany	23 Bundesliga players	HMLD, ACWR, CW	Non-contact injuries	Chronic workload was the strongest predictor of injury compared to acute workload or ACWR.	Narrative only
González et al. (2024)	Spain	24 FC Barcelona Women	Player load + omics	Non-contact injuries	Combining player load with genetic and metabolomic data improved injury risk prediction compared to workload alone.	Narrative only
Herazo-Sánchez et al. (2024)	Colombia	31 pro players	TD, HIRd, sprints	Hamstring injuries	No significant associations were found between external workload and hamstring injuries.	Narrative only
Nilsson et al. (2023)	Sweden	56 youth elite players	Internal & external load	Trauma & overuse injuries	Sudden increases in training load were associated with higher injury risk, while regular sprinting appeared to have a protective effect.	Narrative only

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Table 1. Study characteristics

Authors (Year)	Country	Population	Load Variables	Injury Outcomes	Key Results	Meta-analysis Eligibility
Martins et al. (2023)	Portugal	33 Liga players	TD, HSR, ACC, DEC	Lower-limb injuries	Higher total distance, high-speed running, accelerations, and decelerations in the four weeks before injury were linked to increased risk.	Narrative only
Nobari et al. (2022)	Iran	21 pro players	ACWR, 1-AW	Non-contact injuries	Weeks with high ACWR or acute workload variation were associated with higher risk of non-contact injuries (OR/RR significant).	Included (RR)
Nobari et al. (2021)	Iran	21 pro players	TD, HSD, SPD, RS	Non-contact injuries	High sprint-related loads (total distance, high-speed distance, sprint distance) significantly increased the risk of non-contact injuries (OR/RR significant).	Included (RR)
Jaspers et al. (2018)	Turkey	30 pro players	TD, HSR, s-RPE	Overuse injuries	Greater total distance and higher session-RPE were significant predictors of overuse injuries (OR significant).	Included (OR)
Malone et al. (2018)	Europe	37 elite players	HSR, sprinting, chronic load	Lower-limb injuries	Excessive high-speed running and sprinting loads increased injury risk, while good aerobic fitness and chronic high load had protective effects.	Included (OR)

Abbreviations: TD-total distance; HMLD-high metabolic load distance; Acc/Dec-accelerations/decelerations; ACWR-acute:chronic workload ratio; CW-chronic workload; HIRd-high-intensity running distance; HSR-high-speed running; ACC-accelerations; DEC-decelerations; 1-AW-one-week acute workload; HSD-high-speed distance; SPD-sprint distance; RS-repeated sprint; s-RPE-session rating of perceived exertion. Studies labeled as "Not compatible" or "Insufficient data" were excluded from the quantitative synthesis because they did not provide the minimum numerical information required for effect-size calculation.

Table 2. Quality assessment of included studies – Newcastle–Ottawa Scale (NOS)

Author/Year	Selection	Comparability	Outcome	Total	Risk of Bias
Morgans et al. (2025)	3	1	2	6	Moderate
Zumeta-Olaskoaga et al. (2025)	4	1	2	7	Moderate
Soler et al. (2025)	3	1	2	6	Moderate
Marshall et al. (2024)	3	2	2	7	Low
González et al. (2024)	3	1	3	7	Low
Herazo-Sánchez et al. (2024)	2	1	2	5	High
Nilsson et al. (2023)	3	1	2	6	Moderate
Martins et al. (2023)	3	1	2	6	Moderate
Nobari et al. (2022)	4	2	2	8	Low

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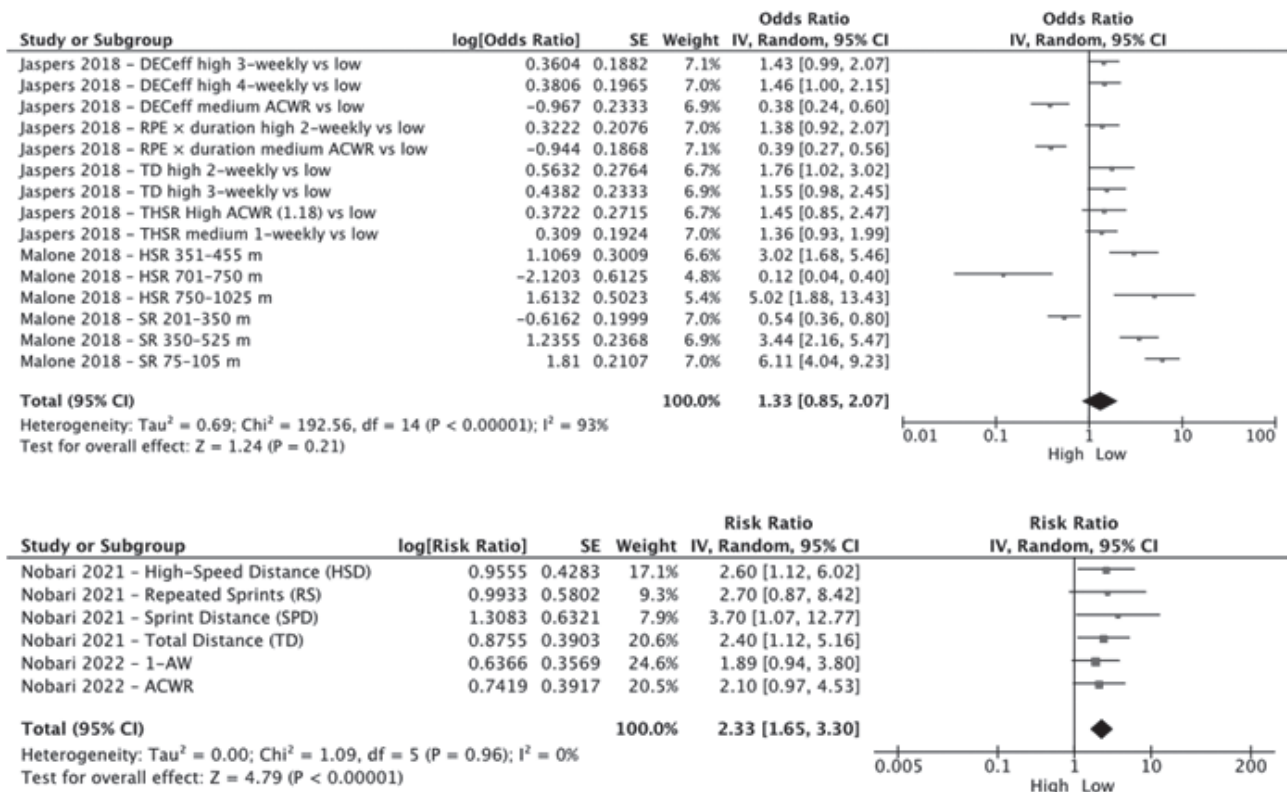
Table 2. Quality assessment of included studies – Newcastle–Ottawa Scale (NOS)

Author/Year	Selection	Comparability	Outcome	Total	Risk of Bias
Nobari et al. (2021)	4	2	2	8	Low
Jaspers et al. (2018)	3	1	3	7	Low
Malone et al. (2018)	3	1	2	6	Moderate

Because the extractable studies used different effect-size metrics (OR vs. RR), two independent meta-analyses were performed. OR-based and RR-based results were therefore interpreted separately to avoid combining conceptually incompatible estimates. A meta-analysis of studies reporting odds ratios (ORs) (Jaspers et al., 2018; Malone et al., 2018) showed no significant association between high training load and increased risk of lower-limb muscle injury (pooled OR=1.33; 95% CI [0.85–2.07], $p=0.21$). Study-specific estimates between studies varied widely (OR ranged from 0.12 to 6.11), reflecting differences in workload definition such as sprint distance, high-speed running, session-RPE, and total distance. Heterogeneity between studies was very high ($Tau^2=0.69$, Chi^2 192.56, p 0.00001, $I^2=93%$), indicating inconsistency in study results. Thus, although some training load indicators showed an increased risk of injury, the combined effect did

not reach statistical significance. It should also be noted that despite the relatively large number of outcomes analyzed (15 OR-based comparisons), these were derived from only two original studies. This limited study base reduces the robustness of the findings and increases the risk of bias, warranting cautious interpretation.

In contrast, studies reporting risk ratios (RRs) (Nobari et al., 2021, 2022) indicated a consistent and robust association between higher workload and injury risk (pooled RR =2.33; 95% CI [1.65–3.30], $p<0.00001$; $I^2=0%$; Figure 2b). These findings suggest that athletes exposed to higher workloads have more than double the risk of injury compared with those with lower exposure. Risk estimates also appeared higher for non-contact injuries than for overuse injuries based on individual study results. However, no formal subgroup pooling was conducted due to the small number of studies.

**Figure 2a.** Forest plot of OR-based studies (upper figure);**Figure 2b.** Forest plot of RR-based studies (lower figure)

The contrast between the non-significant OR-based analysis and the significant RR-based analysis likely reflects differences in workload definitions, thresholding practices, and injury-risk modelling across studies.

A visual assessment of funnel plots was limited because fewer than ten studies were included. For RR-based analyses (Figure 3b), the plot appeared relatively symmetrical, suggesting low potential for publication bias and reasonable consistency across studies. In contrast, the OR-based funnel plot

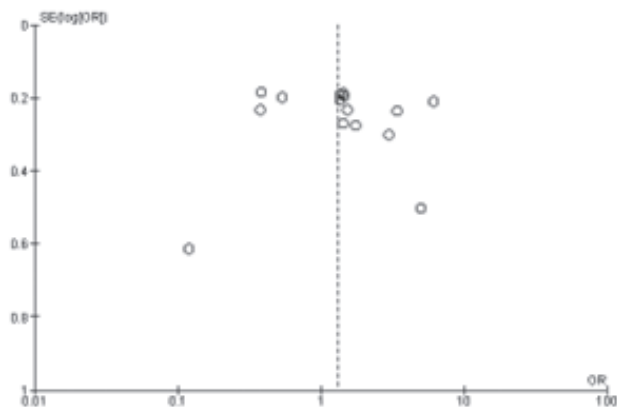


Figure 3a. Funnel plot OR

(Figure 3a) appeared asymmetrical, which may reflect high between-study heterogeneity and possible publication bias. Such asymmetry can arise when smaller studies with significant findings are more likely to be published than those with non-significant results, thereby distorting the pooled effect. Given the small evidence base (<10 studies), these patterns should be interpreted cautiously and do not constitute strong evidence of publication bias.

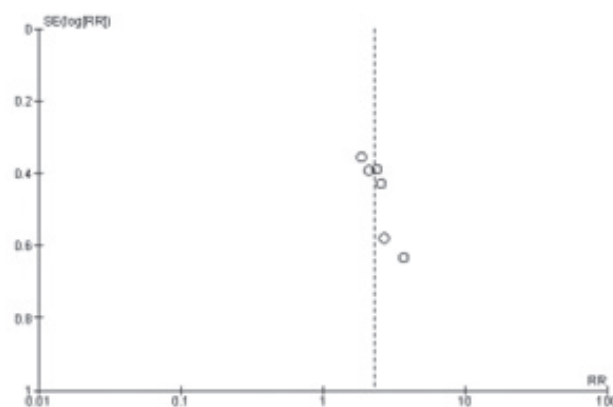


Figure 3b. Funnel plot RR

Discussion

The results of this study indicate that the association between GPS/GNSS- and IMU-derived training load variables and the incidence of lower-limb muscle injuries in football players remains inconsistent. Analysis based on odds ratios (ORs) obtained from the studies by Malone et al. (2018) and Jaspers et al. (2018) showed no significant association between high training load and increased risk of injury (pooled OR=1.33; 95% CI [0.85–2.07]), and exhibited very high heterogeneity. Conversely, analysis using risk ratios (RR) from studies by Nobari et al. (2021, 2022) showed a strong and consistent relationship, where exposure to high loads was associated with more than double the risk of injury (pooled RR =2.33; 95% CI [1.65–3.30]), as well as low heterogeneity. These differing findings warrant cautious interpretation, given the small evidence base, variation in workload definitions, and differences in statistical approaches.

A major challenge in synthesizing the current evidence is the substantial heterogeneity in how external workload is defined and operationalized across studies. Speed thresholds for high-speed running and sprinting vary widely between teams and tracking systems, accelerometry-based variables lack standardized cut-offs, and ACWR is calculated using multiple non-equivalent approaches (e.g., rolling averages vs. EWMA models). These inconsistencies limit the comparability of workload metrics and likely contribute to the divergent findings observed between studies.

The inconsistency between OR and RR based results likely reflects differences in how definitions and selection of workload indicators in each study. For example, Malone et al. (2018) emphasized high-speed running (HSR) and sprinting with various distance cut-off ranges, while Jaspers

et al. (2018) focused on total distance and session-RPE. By contrast, Nobari et al. (2021, 2022) used acute workload, chronic workload, and ACWR, placing greater emphasis on weekly workload fluctuations. Certain variables, such as HSR, high-distance sprinting, and ACWR >1.5, are consistently reported with an increased risk of muscle injury (Malone et al., 2018; Nobari et al., 2021).

Conversely, moderate workload and good physical capacity can be protective. For example, higher aerobic capacity has been associated with reduced injury susceptibility in players with high training loads (Malone et al., 2018).

Physiologically, this can be explained through the concept of muscle fatigue and the accumulation of microtrauma from repeated exposure to sprints, accelerations, and decelerations. Exposure to excessive loads without adequate recovery can reduce the muscles' capacity to absorb external forces, increasing the risk of tissue damage (Carling et al., 2018; Colby et al., 2014). Conversely, when increased loads are applied gradually in accordance with the player's capacity, physiological adaptations can occur, reducing injury risk (Windt & Gabbett, 2017). Taken together, this indicates that the relationship between training load and injury is nonlinear and depends on the balance among external load, physical capacity, and recovery quality.

The findings in this review are consistent with prior work showing that load spikes—sudden increases in training load are important predictors of injury in football players. For example, Colby et al. (2014) found that abrupt increases in GPS-monitored running load correlated with a higher risk of injury in elite players.

A similar finding was reported by Windt et al. (2018), who noted that the relationship between training load and

injury is nonlinear, but rather influenced by the balance between load exposure and individual adaptive capacity. Carling et al. (2018) further observed that accumulating high loads in a short period may lead to neuromuscular fatigue and increased muscle damage, thereby increasing the risk of injury if not balanced with adequate recovery. Thus, although GPS-monitored training load can indicate risk, the relationship is not necessarily linear; it depends on the interaction among load intensity, distribution, and players' physiological capacity to tolerate load.

In practice, monitoring training load with GPS can serve as a warning system for coaches and medical teams by detecting load spikes that may increase injury risk. This information enables rapid adjustments to the training plan to keep load within a player's tolerance. Load management should prioritize preventing spikes and implementing progressive increases aligned with individual physical capacity. Indices such as ACWR can help monitor the balance between acute and chronic load, but they should not be used in isolation. Individual factors—such as age, playing position, and injury history—must also be considered to make prevention strategies more effective and to personalize training programs.

Limitations

Although this review provides an overview of the association between GPS-based workload variables and lower-limb muscle injuries, several limitations should be considered. Multiple effect sizes were extracted from single studies, which may introduce dependency bias despite representing distinct workload variables. The quantitative evidence base was small: of the twelve eligible studies, only four provided extractable numerical data, contributing a total of 21 outcomes—most of which originated from just two primary studies. This limited evidence base reduces the statistical power and stability of the pooled estimates, restricts the possibility of subgroup or sensitivity analyses, and increases vulnerability to bias. Additionally, definitions of workload variables were not uniform (e.g., speed cut-offs for HSR and sprinting, ACWR formulas), inflating heterogeneity and hindering direct comparisons. Most studies were single-club with small samples, limiting generalizability, and publication bias remains possible.

The contrasting results between the OR-based and RR-based analyses further highlight the influence of methodological and definitional variability. The OR meta-analysis showed no significant association and very high heterogeneity, whereas the RR meta-analysis demonstrated a strong and consistent effect. This discrepancy likely reflects differences in how “high workload” was defined, the injury-risk models employed, and the types of workload metrics emphasized across the included studies. As such, differences in effect size metrics should not be interpreted as contradictory findings, but rather as evidence of non-equivalent exposure definitions.

Despite these limitations, the findings suggest that elevated external workloads—particularly when captured through GPS/GNSS metrics such as high-distance locomotor loads or repeated sprint exposures—may increase the risk of lower-limb muscle injuries. However, given the variability in workload definitions and small number of contributing stud-

ies, practitioners should apply these findings cautiously and prioritize individualized monitoring frameworks rather than rigid workload thresholds.

Future research

To address these limitations, future research should use multi-club, multi-season designs with larger samples to improve representativeness. Standardizing the definition and measurement of training load—particularly sprint speed cut-offs, HSR, and ACWR—is essential to improve consistency across studies. In addition, integrating external load (GPS) with internal load (e.g., heart rate [HR] and session-RPE), together with individual factors such as fitness level, injury history, and genetic aspects, can provide a more comprehensive picture of injury risk. Looking ahead, machine-learning-based analytical approaches and predictive modelling (Saberisani et al., 2025), could help generate more accurate and applicable models for injury prevention in professional football.

Conclusion

This systematic review and exploratory quantitative synthesis indicate that GPS-monitored training-load variables are associated with lower-limb muscle-injury risk in football players. However, the available evidence is limited and not entirely consistent. OR-based analyses found no significant association, whereas RR-based analyses showed more than a twofold increase in injury risk among players with high loads. These divergent results suggest that the relationship between training load and injury is nonlinear and influenced by variable definitions, analytical methods, and individual player capacity. GPS monitoring can serve as an early-warning system for coaches and medical teams to manage training load, emphasizing a balance between gradual progression and physical capacity. Nonetheless, the limited number of studies, variations in workload definitions, and small samples highlight the need for further research using multi-club designs, standardized variables, and modern predictive approaches to strengthen the evidence base.

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Conflict of interest

The authors declare no conflicts of interest.

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Kinematic Parameters of the Kick Start: A Systematic Review

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Abstract

This study aimed to analyse recent changes in the kinematic parameters of the kick start. Following PRISMA guidelines, a systematic review was conducted using Web of Science, Scopus, PubMed, and EBSCO. The primary search term kick start was combined with swimming, swimming start, biomechanics, and performance. After screening 665 studies and applying the inclusion criteria, 18 studies analysing kick-start kinematics were included. This research is part of VEGA project No. 1/0462/22, titled "The effect of starting block configuration on the kinematic parameters affecting starting performance in swimming." The review highlights differences across the block, flight, underwater, and swim phases by gender, swimming style, and performance level. Across studies, block time ranged from 0.68–0.91 s in junior swimmers, 0.66–0.72 s in senior swimmers, and 0.59–0.72 s in elite swimmers. Elite swimmers also achieved take-off horizontal velocities of 4.37–4.58 m·s⁻¹. The start performance at 15 m was 6.31–6.72 s in senior and 6.33–6.41 s in elite swimmers compared with 6.94–7.09 s in junior competitive swimmers, with women being approximately 1 s slower. Technique modifications associated with faster early-race performance consistently included kick-plate settings 3–4 and neutral-/rear-weighted set positions; a narrow stance improved time to 5 m by 0.08 s compared with a wide stance, and faster starters demonstrated a higher hip position at the start signal (1.56±0.05 m vs. 1.45±0.05 m). Findings provide valuable insights for swimmers and coaches, aiding in technique refinement. Given its use in elite competitions, optimising the kick start can lead to measurable performance gains, reinforcing the need for targeted training approaches.

Keywords: *biomechanics, performance, phase, kick plate, starting platform, starting block*

Introduction

Performance in sprint swimming disciplines is continually advancing, resulting in new milestones such as the 50-meter freestyle, where, for the first time in swimming history, Jordan Crooks from the Cayman Islands completed the race in under 20 seconds (19.90 s), setting a new world record at the 2024 World Championships in Budapest (WA, 2024). The swimming start is defined as the interval from the start signal to the moment the swimmer's head crosses the 15-meter mark (Cossor & Mason, 2001). A key aspect of this performance is the start (the first 15 meters), which is continuously evolving in the search for the optimal starting technique that allows swimmers to achieve the shortest possible time, particularly in sprint disciplines (Barlow et al., 2014; Tor et al., 2015). The technical execution of the swimming start is closely linked to the history of swimming performance and to the modernisation of starting blocks at elite swimming events (Taladriz Blanco et al., 2017). Initially, swimmers used the grab start technique, followed by the track start, and currently, with the

introduction of the new Omega OSB11 starting block (since 2009), which features an adjustable kick plate, swimmers use the kick start technique. This new starting block offers a position similar to the track start, with the advantage of placing the rear lower limb on a stable kick plate (adjustable to positions 1–5), which each swimmer can customise according to their preferences (Rundik et al., 2022; Swiss Timing, 2019). Ozeki et al. (2012) report a shorter time to 15 meters (0.14 s) in elite swimmers using the kick start technique than with the track start. Since the kick-start technique is now used at all major competitions, the grab-start and track-start techniques are becoming obsolete. Some studies have focused on evaluating the start without undulation and the first swimming movements at 5 meters (Matúš et al., 2022; Matúš et al., 2024b; Silveira et al., 2018). These studies aimed to assess the effectiveness of the basic position on the starting block in relation to time at 5 meters. Other studies have evaluated the start at 10 meters (Djurkovic et al., 2019) and 15 meters (Qiu et al., 2021; Rudnik et al., 2021; Rudnik et al., 2023; Sanchez et al., 2021; Shepherd et al., 2023), where at 15 meters,

the start as a whole was assessed in terms of the individual phases that follow one another – above-water phase (block and flight phase), underwater phase, and swim phase. The swim phase varies by stroke, with breaststroke swimmers exhibiting a longer underwater phase than freestyle swimmers (Matuš et al., 2024a; Matuš et al., 2024c). In the block phase, various studies have focused on the basic position on the starting block (Matuš et al., 2020; Matuš & Kandrác, 2020; Rudnik et al., 2022; Wardzyk et al., 2022). Optimisation has mainly focused on the basic setting of the kick plate and the swimmer's body position. In terms of phase duration, this is the second-shortest phase contributing to performance at the start, but it is also the initial phase that can influence performance in subsequent phases (Tor et al., 2014). Some studies recommend setting the kick plate to the 3-4 level with a neutral- or rear-weighted basic position (Matuš et al., 2020; Matuš et al., 2022; Matuš & Kandrác, 2020). Other studies suggest placing the stronger or non-preferred lower limb on the kick plate (Burkhard et al., 2020; Matuš et al., 2022), as swimmers with their preferred lower limb placed at the front edge of the starting block achieved a shorter time to 5 meters (Matuš et al., 2022). In Matuš et al. (2024b), narrow and wide positions were evaluated, with performance swimmers achieving shorter times to 5 meters in the narrow position. In the above-water phase, block time and take-off velocity were identified as reliable parameters for start-ups at 15 meters (Burkhard et al., 2020). Djurkovic et al. (2019) also reported a positive effect of block time on 10-meter time. The underwater phase, in terms of time, is one of the longest phases of the start (Tor et al., 2014). Djurkovic et al. (2019) noted the impact of underwater time on 10-meter time, where, in freestyle on the 50 meters, intersex differences were more evident in underwater time ($p < 0.01$) than in underwater distance ($p < 0.05$). Swimmers at depths of -0.9 to -1.1 meters achieved shorter times at 5 and 15 meters. The kinematic outcomes of the swimming start may vary across swimmer characteristics and race demands. However, evidence on kick-start kinematics is currently fragmented across studies that assess different distances (e.g., 5, 10, and 15 m), apply inconsistent phase definitions, and report heterogeneous outcome measures, which limits direct comparison and clear practical interpretation. Therefore, an up-to-date synthesis is needed to systematise the available findings and identify consistent patterns and remaining gaps in the literature. This study aimed to analyse recent changes in kinematic parameters of the kick-start technique. Based on this objective, 18 studies analysing kinematic parameters in the kick start were selected and reviewed. With this aim, the results in the discussion were divided into four phases – block, flight, underwater, and swim phase – from the perspectives of sex, stroke type, and performance.

Material and methods

The systematic review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Haddaway et al., 2022). This systematic review was registered in the International Prospective Register of Systematic Reviews (PROSPERO) under registration number CRD420251268896.

Search strategy

Data acquisition and processing consisted of several steps. The first step was to search the available resources related to our review study. The search was made in November 2024 and was restricted based on the publishing year. To obtain information concerning selected kinematic characteristics of kick start, was used scientific articles registered in databases: Web of Science, Scopus, PubMed, Ebsco. Consequently, the main search term keyword was kick start together with the following keywords and their combinations: swimming, swimming start, biomechanics, performance.

Inclusion and exclusion criteria

The results of the database searches were entered into the web-based programme Rayyan.ai (Ouzzani et al., 2016), which was used to screen the abstracts independently by all authors. The inclusion criteria for studies included in the systematic review were as follows: (a) the study was published in 2019-2024; (b) paper with an experimental analysis, which reported quantitative results of the analyzed variables; (c) studies involved the swimming sport reporting results of kick start techniques; (d) high competitive level of the sample, elite or international and national swimmers; (e) human participants without diseases of pathologies (f) written in English. Articles were excluded for the following reasons: (a) data aside kinematic characteristic; (b) irrelevant data for analysis; (c) unavailable full text; (d) duplicates; (e) systematic review. The included studies analysed the start performance by examining the block, flight, underwater, and swim phases, with respect to sex, stroke type, and performance level.

Data extraction, quality assessment and risk of bias

Two independent reviewers performed the search, screened the titles and abstracts from the search results using the web-based programme The Rayyan.ai (Ouzzani et al., 2016) and reviewed the selected full texts before inclusion. The sample size, the objectives and the main results of the kinematic characteristic of kick start were extracted from each selected study. Quality assessment was performed by two reviewers (K.N.; T.E.). A third reviewer was consulted to resolve any disagreements (I.M.).

The methodological quality and risk of bias of the included studies were independently assessed by two reviewers using the National Institutes of Health (NIH) Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies. This tool consists of 14 items evaluating key sources of bias, including clarity of the research question, study population definition, participant selection, sample size justification, outcome measurement validity and reliability, and appropriateness of statistical analyses. Each item was rated as "Yes", "No", or "Cannot determine/Not reported/Not applicable". Based on the overall assessment, studies were classified as good, fair, or poor quality, reflecting their overall risk of bias. Any disagreements between reviewers were resolved through discussion. When consensus could not be reached, a third reviewer was consulted.

Variables definitions

Several definitions of temporal, kinematic and kinetic variables have been used for a detailed biomechanical analysis of the swimming kick-start. In order to clarify the infor-

mation provided in this systematic review, a definition of the most common variables used in the different studies was provided (Table 1).

Table 1. Variables definition

Phase	Variables	Units	Definition	
Block phase	Front knee angle	FKA	°	Hip/ankle at the set position
	Front ankle angle	FAA	°	Knee/ankle/finger toe at the set position
	Rear knee angle	RKA	°	Hip/ankle at the set position
	Rear ankle angle	RAA	°	Knee/ankle/finger toe at the set position
	Hip angle	HA	°	Ankle/hip/shoulder
	Block time	BT	s	Starting signal—feet separation from the platform
	Reaction time	RT	s	The time interval between the starting signal and a change in starting block reaction force curve as a result of the initial movement
	Hands take-off	HTo	s	The time interval between the starting signal and the last contact of the hands with the starting block
	Hands take-off: reaction time	HTR	s	The time interval between the starting signal and the last contact of the hands with the starting block, reduced by the reaction time
	Rear foot take off	RFT	s	The time interval between the starting signal and the last contact of the rear foot with the starting block
	Rear foot take off: reaction time	RFTR	s	The time interval between the starting signal and the last contact of the rear foot with the starting block, reduced by the reaction time.
	Front foot support	FFS	s	The time interval between the last contact of the rear foot with the starting block and the moment when total vertical force fell to zero
	Movement time	MT	s	The time interval from the first visible change in starting block reaction force curve and the instant when total vertical force fell to zero
	Take off horizontal velocity	Vx	m/s	Magnitude of the horizontal velocity of the CoM vector at take-off
Take off vertical velocity	Vy	m/s	Magnitude of the vertical velocity of the CoM vector at take-off	
Take off velocity	Vt	m/s	The total velocity of swimmer's centre of mass at the instance of take-off.	
Flight phase	Entry angle	EA	°	Horizontal/fingertips/hip joint
	Entry velocity	EV	m/s	The horizontal velocity which the swimmer travels through the air during the entry phase.
	Take-off angle	TA	°	Ankle/hip/horizontal
	Take-off head position	HP	m	Water surface/head
	Time to 2 m	T2	s	Starting signal/head crosses the 2 m
	Flight time	FT	s	Take-off/hand entry
	Flight distance	FD	m	Take-off/hands touch the water
	Flight velocity	FV	m/s	Mean horizontal head velocity at time from loss of contact with starting block to submersion of head in water
Underwater phase	Glide time	GT	s	Hand entry/head crosses the 5 m
	Glide distance	GD	m	Hands touch the water/head crosses the 5 m
	Glide velocity	GV	m/s	Mean horizontal head velocity during glide phase
	Maximal depth	MaxH	m	Head reaches the maximum depth
	Time to 5-m	T5	s	Starting signal—head crosses the 5 m
	First kick time	FKT	s	Time from the swimmer's fingers first touching the water to the moment they completed the first underwater down kick.
	First kick distance	FKD	m	The horizontal distance between the wall and swimmer's head when they completed the first underwater down kick.
	Underwater time	UWT	s	The time of the first contact of the swimmer's hands with the surface of the water until the swimmer's head breaks the surface of the water.
Underwater distance	UWD	m	The distance of the first contact of the swimmer's hands with the surface of the water until the swimmer's head breaks the surface of the water.	

(continued from previous page)
Table 1. Variables definition

Phase	Variables	Units	Definition	
Swim phase	Time to 10-m	T10	s	Starting signal–head cross the 10 m
	Time to 15-m	T15	s	Starting signal–head cross the 15 m
	Time 5- 10-m	T 5-10	s	The time interval between the moment when the head crossed the 5-m mark and the moment when the head reached the 10 m distance from the starting line
	Time 10-15-m	T 10-15	s	The time interval between the moment when head crossed the 10-m mark and the moment when the head reached the 15-m distance from the starting line
	Swim time to 15 m	ST	s	The time of the swim from the time the swimmer’s head crosses the surface of the water until the swimmer’s head has again crossed the 15 m distance
	Swim distance to 15 m	SD	m	The distance of the swim from the time the swimmer’s head crosses the surface of the water until the swimmer’s head has again crossed the 15 m distance.

Results

Data search and characteristics of the studies

A total of 665 studies were screened; after applying the

inclusion criteria, 18 studies were included in the systematic review. The screening and selection processes are shown in Figure 1.

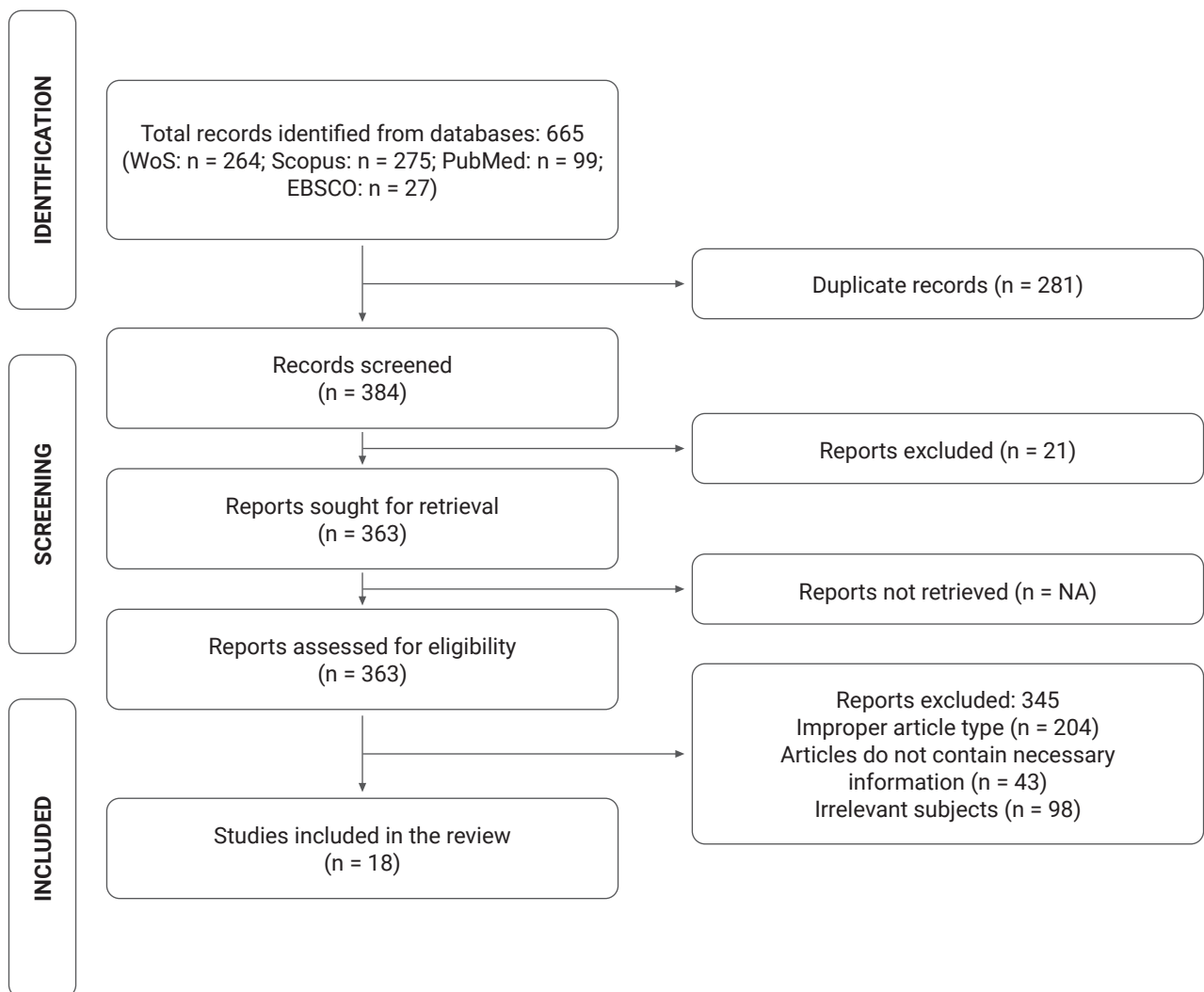


Figure 1. Prisma Flow diagram

Quality of the Studies

The methodological quality of the included studies was generally high. According to the NIH Quality Assessment Tool, 12 studies were rated as good quality and 6 as fair quality. No study was classified as poor. The most common sources of potential bias were the absence of sample size justification, relatively small sample sizes, and limited reporting

of assessor blinding. In contrast, outcome measurement bias was considered low, as the majority of studies used validated biomechanical measurement systems (e.g., force plates, high-speed cameras, and 3D motion analysis). Overall, the risk of bias across studies was judged as low to moderate and was unlikely to substantially affect the main conclusions of this review (table 2).

Table 2. Methodological quality and risk of bias assessment of included studies (NIH tool)

Study	Study design	NIH score (0–14)	Quality rating	Overall risk of bias
Djurovic et al. (2019)	Cross-sectional	10	Good	Low–moderate
Burkhardt et al. (2020)	Cross-sectional	11	Good	Low
Cicenia et al. (2020)	Cross-sectional	9	Fair	Moderate
Matuš et al. (2020)	Cross-sectional	10	Good	Low–moderate
Matuš & Kandráč (2020)	Cross-sectional	10	Good	Low–moderate
Qiu et al. (2021)	Cross-sectional	11	Good	Low
Matuš et al. (2021a)	Cross-sectional	10	Good	Low–moderate
Matuš et al. (2021b)	Cross-sectional	10	Good	Low–moderate
Sánchez et al. (2021)	Cross-sectional	11	Good	Low
Matuš et al. (2022)	Cross-sectional	9	Fair	Moderate
Rudnik et al. (2022)	Cross-sectional	11	Good	Low
Wardzyk et al. (2022)	Cross-sectional	9	Fair	Moderate
Hyodo & Wada (2023)	Cross-sectional	8	Fair	Moderate
Rudnik et al. (2023)	Cross-sectional	11	Good	Low
Shepherd et al. (2023)	Cross-sectional	10	Good	Low–moderate
Matuš et al. (2024a)	Cross-sectional	11	Good	Low
Matuš et al. (2024b)	Cross-sectional	10	Good	Low–moderate
Matuš et al. (2024c)	Cross-sectional	11	Good	Low

Summary of included study

The studies focused on the start, block, flight, underwater, and swim phases, considering factors such as sex, stroke type, and performance level. A detailed summary of each in-

cluded study is presented in Table 3.

Tables 4 and 5 present detailed values of individual kinematic parameters in the block, flight, underwater and swim phases by sex.

Table 3. Summary of each study included in the review

Authors	Subjects	Objective	Kinematics	Start block	Main results
Djurović et al. (2019)	25 male, competitive	Examine the influence of starting parameters on time to 10 m which determines the efficiently executed swimming start.	RT, FT, FD, FV, EV, UWT	SO2-X starting block	The results indicated the significant statistical influence of all system of predictors variables on swimming start up to 10 m (F=1353.9, p=0.000). Influence of starting parameters in the function of the swimming start efficiency are represented by: Under-water time (t=66.1, p=0.000). Entry_Velocity (t=-13.174, p=0.000). Flight_time (t=9.541, p=0.000). Reaction_time (t=2.877, p=0.010). Flight_distance (t=-2.667, p=0.016) and Flight_Velocity (t=2.528, p=0.021), respectively.
Burkhardt et al. (2020)	15 (13 male, 2 female), competitive	Investigate the reliability of the KISwim with its kinematic and kinetic parameters and to identify the Key Performance Indicators for the kick-start using a Principal component analysis; to determine whether the most beneficial position of the strong leg is in the front or at the back of the starting block and investigate the effect of an acute reversal of the leg positioning.	T1.5BT, MaxH, 7.5, Vx	Omega OSB 11 starting block	Kinematic and kinetic parameters showed high reliability (ICC>0.75) from which principal component analysis identified seven KPI (i.e., time to 15 m, time on-block, depth at 7.5 m, horizontal take-off velocity, horizontal impulse back plate, horizontal peak force back plate and vertical peak force front plate). For the preferred start position, the back plate showed a higher horizontal peak force (0.71 vs. 0.96 x body mass; p<0.001) and impulse (0.191 vs. 0.28Ns/BW, p<0.001) compared to front plate. Plate-specific kinetic analysis revealed a larger horizontal peak force (p<0.001) and impulse (p<0.001) for the back compared to the front plate in any start position investigated.
Cicenia et al. (2020)	20 (8 female, 12 male), elite	Use shin length as a measure to determine kick plate position and effects on performance.	RT, BT, FT, FD, UWT, T15, RKA, RAA	-	BT was significantly different, (F(2,38)=4.264, p=0.026). BT was lower when the kick plate distance was one shin length versus shin length (0.691±0.055 vs 0.715±0.056 sec) and shin length (0.691±0.055 vs 0.698±0.056 sec), p<0.05.
Matuš et al. (2020)	10 male, competitive	Determine differences in the front and rear knee angles depending on the body and kick plate positions during the kick start from OSB12.	BT, FKA, RKA, TA, EA, FD, GD, T5	OSB12 starting block	Changes in all studied swim start parameters between the front-weighted position and rear-weighted position for all kick plate positions (p<.05). Swimmers produced shorter times to 5 meters when the front knee angle and rear knee angles in the starting position ranged from 1300 - 1320 and 760 - 820, respectively. The rear-weighted position produced higher takeoff and entry angles, shorter glide distance than the front-weighted or neutral-weighted position.
Matuš, Kandrác (2020)	8 male, performance-level	Determine kinematic parameters underlying the kick start from OSB12 in terms of the kick plate position and shoulder positioning at the start.	FKA, RKA, HA, BT, EA, TA, HP, T2, FT, FD, G1GD, MaxH	OSB12 starting block	Significant differences (p<0.05) in the selected kinematic parameters in all phases, which depended on the OSB12 kick plate position and basic starting position (front-, neutral-, and rear-weighted). The greatest differences in the parameters measured were found between the front-weighted start and rear-weighted start.
Qiu et al. (2021)	12 male, elite	To compare the kinematic characteristics of individual and relay swimming starts and to relate the kinematic variables of both starts to the 5 m start performance.	BT, FT, Vx, Vy, Vt, EA, EV, TA, FT, MaxH, MaxHT, T5, FKT, FKD, UWT, UWD, T10	Omega OSB11 starting block	The results indicated moderate to much faster 5 m, 10 m, 15 and 15 m times (29.4, 10.7 and 6.5%) for relay than individual starts as well as the differences at specific parameters, but no differences in take-off horizontal velocity between start techniques. Large correlations to performance times were found in block time, horizontal take-off velocity, take-off velocity and entry angle (r=0.77 to 0.83), 20 for individual start, but in changeover time, take-off height and entry distance (r=0.69 to 0.90) for relay start. Differences on swim start regulations between individual and relay events were in line with different key parameters related to start performances in each event.
Matuš et al. (2021)	18 male, competitive	Determine the key parameters affecting kick start performance expressed as the time to 5 m without underwater undulating and kicking. And to identify the contribution of particular start phases to the time to 5 m.	FKA, RKA, FAA, RAA, HA, SP, BT, EA, TA, HP, T2, FT, FD, GT, GD, MaxH, T5	OSB12 starting block	Significant correlations (p<0.01) between the front ankle angle and block time was found. Statistically significant correlations (p<0.01) between block time and rear ankle angle, respectively, to time to 2 m; rear-knee angle and glide time; block time and time to 5 m; time to 2 m and time to 5 m; and flight distance and glide distance. The multiple regression analysis showed that the on-block phase and flight phase parameters, respectively, contributed 64% and 63% to the time to 5 m.
Matuš et al. (2021)	20 females, competitive	Examine differences in starting and kick-plate positions, pointing to an effect on kick-start performance with the dominant and non-dominant feet placed on the front edge of the OSB12 starting block.	FKA, FAA, RKA, RAA, HA, BT, TA, HP, T2, EA, FT, FD, GT, GD, MaxH, T5	OSB12 starting block	The results demonstrate the importance of leg dominance and positioning on the OSB12 starting block. When the dominant leg was placed on the front edge of the starting block (p<0.05; Cohen's d=large effect), swimmers produced shorter block times and times to 2 and 5 m. For most of the tested swimmers, the optimal basic position on the starting block included neutral- and rear-weighted positions with the kick plate set to positions 3-4 and the right leg placed on the front edge of the OSB12 starting block.
Sánchez et al. (2021)	234 (132 male, 102 female), national	Analyse the influence of the breaststroke underwater phase on 50 and 100m performance.	T15	-	High correlations were obtained for both events and genders between start time and final time (r=0.76-0.91). The emersion velocity was higher in 50 m than in 100 m (p<0.001; d=1.0) and in 70 males (50m: 2.18±0.10 m·s ⁻¹ ; 100m: 1.87±0.08 m·s ⁻¹) than in females (50 m: 1.92±0.09 m·s ⁻¹ ; 100 m: 1.71±0.08 m·s ⁻¹). Performance in both events was influenced significantly by turn velocity (r≥0.85), and combined with the start, contributed to around 55% of the final time.
Matuš et al. (2022)	12 male, competitive	Identify correlations between jumping abilities and time to 5-m distance during the OSB12 kick start.	FKA, FAA, RKA, RAA, HA, SP, BT, EA, TA, HP, T2, FT, FD, GT, GD, MaxH, T5	OSB12 starting block	For THTR, a correlation with time to 5-m distance was observed (p<0.05). There was a correlation (p<0.05) between SJ and time to 5-m distance. For CMJRA, a correlation with time to 5-m distance was observed (p<0.05). The highest correlation (p<0.01) was found between CMJRA and time to 5-m distance.

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Table 3. Summary of each study included in the review

Rudnik et al. (2022)	38 (19 males, 19 females), international	Evaluate the ventral start performance using different back plate positions and to observe the eventual movement pattern adaptations of swimmers associated with those changes.	BT, RT, Hto, RFT, RFT, FFS, MT, T15	OMEGA OSB 14 starting block	In males, the 15 m start time was 0.1 s shorter for the preferred position compared with the backward position (p<0.05). Regardless of the back plate positioning, the swimmers spent a similar time on the block. A more forward position of the back plate postponed the rear foot take-off and consequently reduced the front foot stand duration. A back plate position effect was revealed for those variables with a larger effect size in males whereas in females, a change of about two positions was needed to reach a significance level.
Wardzyk et al. (2023)	20 male, -	Analyse kinematic parameters of above- and underwater kick start phases among young male swimmers.	FKA, RKA, BT, EA, TA, FT, FD, GT, GD, GV, MaxH, T15	OSB11 starting block	Fs and ss demonstrated differences (p<0.05) regarding hip joint height at starting signal (1.56±0.05 m vs. 1.45±0.05 m), push-off angle (23.89±6.50° vs. 35.12±3.43°), hip joint angle upon completing push-off (163.83±8.37° vs. 149.73±9.93°), and horizontal velocity during flight (3.70±0.35 m/s vs. 3.24±0.22 m/s), submerison (4.88±0.09 m/s vs. 4.36±0.22 m/s), and glide phase (3.40±0.17 m/s vs. 2.99±0.29 m/s)
Hyodo, Wada (2023)	14, not mention	Clarify the effect of the presence or absence of upper limb movement on the propulsion direction body velocity (TPV) leaving the platform at kick start.	Vy, TA	SEIKO starting block	In the movement speed at the time of leaving the platform, the standard trial had a significantly higher value in the propulsion direction and a significantly lower value in the vertical movement speed than the lower trial. The standard trial had a significantly lower value in the jumping angle when leaving the platform, the role of the upper limb movement in kick start is to promote by making the jumping angle closer to the horizontal when leaving the platform.
Rudnik et al. (2023)	52 (22 male, 30 female), international	Explore sex diversity with regard to the variability of the spatiotemporal variables of the kick-start technique and to determine the effect of sex heterogeneity on the biomechanical characteristics of swimming start by investigating the determinants of its performance.	FKA, FAA, RKA, RAA, HA, BT, TA, HP, T2, EA, FT, FD, GT, GD, MaxH, T5	OMEGA OSB 14 starting block, replica	A sex effect was exposed for temporal variables describing all swimming start phases (p<0.015). Male swimmers, by spending less time during the push-off from the starting block (p=0.002; np2=0.18), reaching higher take-off velocity (p<0.001; np2=0.29), traveling longer distances during flight (p<0.001; np2=0.40), and swimming faster in the water phase (p<0.001; np2=0.40). Male participants were faster than females (p<0.001; np2 ≥ 0.40). Significant correlation between variables describing overall starting performance (5-m, 10-m, and 15-m times), and variables commonly highlighted as starting performance determining factors (block phase duration, take-off horizontal velocity, and flight distance) was found in male.
Shepherd et al. (2023)	24 (14 female, 10 male), elite	Understand how a swimmer's body segment orientations and mass centre velocity at toe off, entry distance and flight time affect start performance.	Vx, Vy, FT, T5, T10, T15	-	Whilst time to 5 m (starting performance) differed by 0.17 s between genders, body position at toe off showed no significant differences. The difference in start performance was mainly due to a difference in horizontal velocity at toe off. The relationship between arm angle and start performance warrants further investigation as there was a range of techniques adopted but no clear link to performance. The trunk angle at toe off was correlated to starting performance for both males and females.
Matuš et al. (2024)	194 (99 male, 95 female), national	Show the differences in kinematic parameters of the start and performance in the sprint event of 50 m breaststroke from the perspective of gender in different age groups at international competitions organized in Slovakia.	BT, FT, FD, UWT, UWD, ST, SD, T15	OSB 11 starting blocks	Statistically significant differences (p<0.01) in females were found in the above-water phase in BT, FT, and FD between K3 and K1. The underwater phase in UWT showed differences between K3 to K1, K2 to K1 whereas for UWD - between K3 and K2 and between K2 and K1. For T15 and T25, there were differences (p<0.01) between all categories, but in the final time (T50), the differences occurred between K3 and K2 and between K3 and K1. In males, there was a significant difference in the above-water phase between K3 and K1 and between K2 and K1. In UWD, ST, SD, T15, T25, and T50, there were significant differences between all categories. Differences (p<0.01) between males and females by category in the above-water phase were measured in FT (K1) and FD (K2, K1). In the underwater phase, the differences were found in UWT (K2) and UWD (K1). For T15, T25, and T50, significant differences were shown in all categories.
Matuš et al. (2024)	15 male, competitive	Analyze the effect of the foot in the base position on the block start on performance in the 5 m distance start.	FKA, FAA, RKA, RAA, HA, BT, EA, TA, T2, FT, FD, GT, GD, MaxH, T5	OSB 12 starting blocks	Swimmers were found to have significant differences (p<0.05) between foot widths in block time (0.02 s), time to 2 m (0.05 s), flight and glide time and distance, maximal depth, and time to 5 m (0.08) in favor of the narrow baseline position.
Matuš et al. (2024)	369 (189 males, 180 females)	Reveal the differences in kinematic parameters of start and performance in the sprint 50 m freestyle discipline based on gender in different age categories of competitive swimmers at international competitions organized in Slovakia.	BT, FT, FD, UWT, UWD, T15, ST, SD	OSB 11 starting blocks	In the phase above water level, there were greater differences (p<0.01) in females than in males. Inter-sex differences (p<0.01) were evident in FT in K3, K2 and in FD across all categories. In the underwater phase, differences (p<0.01) were evident in both sexes. Inter-sex differences were more evident in UWT (p<0.01) than UWD (p<0.05). There were inter-sex differences (p<0.01) in ST and SD between all categories except K3. At T15, T25 and T50, differences (p<0.01) were most pronounced between K3 and K2, K1 in females and between all categories in males. Inter-sex differences (p<0.01) were also evident across all categories.

Table 4. Kinematic characteristics of male swimmers

Authors (year)	Djurković et al. (2019)	Matuš et al. (2020)	Matuš, Kandrác (2020)	Qui et al. (2021)	Matuš et al. (2021)	Sánchez et al. (2021)	Matuš et al. (2022)	Rudnik et al. (2022)	Wardzyk et al. (2022)	Rudnik et al. (2023)	Shepherd et al. (2023)	Matuš et al. (2024)	Matuš et al. (2024)	Matuš et al. (2024)
Participants (number, level)	25, competitive	10, competitive	8, performance level	12, elite	18, competitive	61, national	12, competitive	19, international	20, not mention	22, international	10, elite	15, competitive	56, competitive	68, competitive
Years of participants	21.5± 3.6	17.5± 1.9	17.4± 1.8	16.3± 1.4	17.8± 1.5	23.2± 5.1	21.7± 3.9	20.8± 4.2	16.8± 0.80	18.3± 1.8	22± 4	17.0± 2.0	13/14	15/16
Position on starting block	-	Rear-weighted, position 3	Rear-weighted, position 3	-	Rear-weighted, position 3	-	Preferred	Preferred Backward	Rear-weighted, position	-	-	Narrow	Wide	-
Other characteristics	-	Fast time to 5-m	Fast time to 5-m	-	-	50-m Breastsroke	100-m Breastsroke	-	Faster starters, freestyle	Slower starters, freestyle	-	50-m Breastsroke	-	50-m Freestyle
FKA (°)		132.82± 1.13	132.70± 1.8		133.20± 1.4		132.10± 1.1		132.32± 12.95	119.81± 9.71		133.19± 3.08	132.67± 3.26	
FAA (°)					128.40± 0.90		127.20± 0.80					127.33± 4.52	126.84± 4.58	
RKA (°)		79.44± 1.34	79.50± 1.20		79.50± 1.10		78.50± 1.00		90.47± 9.07	87.25± 6.81		82.45± 2.40	82.06± 2.35	
RAA (°)					96.60± 1.70		95.10± 1.50					100.03± 3.31	99.41± 3.44	
HA (°)			44.90± 1.30		44.70± 1.00		43.60± 1.00					43.70± 2.02	43.40± 1.63	
SP (°)					5.70± 0.50		5.50± 0.40							
BT (s)		0.88± 0.07	0.91± 0.07	0.59± 0.05	0.79± 0.06		0.80± 0.08	0.71± 0.04	0.83± 0.04	0.89± 0.09		0.72± 0.12	0.66± 0.10	0.66± 0.09
RT (s)	0.72± 0.08							0.17± 0.04	0.18± 0.03	0.17± 0.03		0.77± 0.03	0.71± 0.13	0.71± 0.09
HTo (s)								0.45± 0.07	0.46± 0.08	0.45± 0.07		0.79± 0.02	0.71± 0.13	0.68± 0.06
HTR (s)								0.28± 0.07	0.28± 0.08	0.28± 0.07				
RFT (s)								0.61± 0.04	0.62± 0.05	0.59± 0.05				
RFT (s)								0.45± 0.05	0.44± 0.04	0.42± 0.04				
FFS (s)								0.11± 0.02	0.12± 0.02	0.13± 0.02				
MT (s)								0.56± 0.05	0.56± 0.04	0.55± 0.05				
Vx (m/s)				4.08± 0.26										
Vy (m/s)				-0.35± 0.42										
Vt (m/s)				4.11± 0.25										

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Table 4. Kinematic characteristics of male swimmers

EA(°)	38.28± 0.97	37.70± 1.10	220.81± 2.58	37.50± 0.90	36.50± 0.80	39.98± 10.48	43.54± 1.70	37.30± 4.00	36.80± 0.85	36.69± 1.35
EV (m/s)	5.16± 0.60		5.40± 0.25							
TA	39.94± 1.13	40.60± 1.30	184.90± 5.82	40.60± 1.50	39.80± 1.20	23.89± 6.50	35.12± 3.43	33.80± 4.40	39.77± 2.39	39.67± 2.67
Flight phase (°)										
HP(m)	1.33± 0.01	1.30± 0.00	1.30± 0.00	1.30± 0.00	1.20± 0.00				0.94 ± 0.02	0.99± 0.02
T2 (s)	1.05± 0.06	1.50± 0.05	1.50± 0.05	1.50± 0.05	1.06± 0.05				0.37± 0.01	0.41± 0.01
FT (s)	0.30± 0.07	0.35± 0.03	0.30± 0.05	0.35± 0.03	0.36± 0.03	0.32± 0.08	0.39± 0.03	0.29± 0.04	0.29± 0.10	0.27± 0.10
FD (m)	3.03± 0.18	2.75± 0.11	2.74± 0.11	2.73± 0.11	2.71± 0.10	2.92± 0.22	2.80± 0.15	2.83± 0.20	2.84 ± 0.18	2.93± 0.18
FV (m/s)	10.61± 2.23								0.69± 0.07	0.71± 0.07
GT (s)	0.53± 0.05	0.52± 0.05	0.55± 0.04	0.55± 0.04	0.57± 0.03	0.43± 0.11	0.48± 0.26		0.52± 0.02	0.55± 0.02
GD (m)	2.25± 0.13	2.26± 0.11	2.27± 0.11	2.27± 0.11	2.29± 0.10	1.46± 0.33	1.38± 0.61		2.31± 0.07	2.39± 0.07
GV (m/s)						3.40± 0.17	2.99± 0.29			
MaxH (m)		-0.91± 0.03	-0.73± 0.00	-0.90± 0.02	-0.89± 0.03	1.50± 0.55	1.33± 0.52		-0.89± 0.02	-0.92± 0.02
T5 (s)	1.76± 0.07	1.79± 0.09	1.60± 0.12	1.70± 0.08	1.73± 0.07			1.53± 0.12	1.67± 0.03	1.75± 0.03
FKT (s)			1.01± 0.26							
FKD (m)			5.40± 0.48							
UWT (s)	3.32± 0.25		3.65± 0.84					4.24± 0.80	4.70± 0.78	4.67± 0.41
UWD (m)			7.71± 1.71					6.66± 1.92	8.50± 1.18	9.53± 1.75
T10 (s)	3.98± 0.23		4.41± 0.38					3.51± 0.24		
T15 (s)			7.20± 0.57			6.51± 0.39	6.72± 0.37	6.41± 0.47	6.33± 0.55	6.43± 0.49
T5-10 m (s)								6.41± 0.45	6.41± 0.45	6.41± 0.45
T10-15 m (s)								2.35± 0.18	2.35± 0.18	2.35± 0.18
ST (s)								4.34± 0.78	2.96± 0.74	1.89± 0.40
SD (m)								5.56± 1.81	3.57± 1.08	2.41± 1.66
								4.24± 0.93	6.95± 1.53	5.15± 1.52
								2.95± 0.90	7.09± 0.66	2.35± 0.69
								6.81± 1.51	7.52± 1.49	4.28± 1.12

Discussion

The purpose of this systematic review was to synthesise recent evidence on kinematic determinants of the swimming kick start by integrating findings from 18 eligible studies. The evidence was organised according to the main start phases (block, flight, underwater, and swim) and interpreted with respect to key moderators reported in the literature, including sex, stroke type, performance level/age category, and starting block/platform configurations. Across studies, start performance (typically assessed at 5–15 m) was most consistently associated with above-water parameters, including block time/reaction-related measures, take-off horizontal velocity, and flight distance/entry characteristics. In comparison, the underwater phase accounted for the largest proportion of time from 15 m and was particularly influential in stroke-specific contexts (e.g., breaststroke). However, direct comparability between studies is constrained by methodological heterogeneity (tested distance, phase definitions, and starting block models), which should be considered when translating these findings into applied settings.

Block phase

The block phase can be characterized as the time from the start signal until the swimmer's feet leave the starting block. The percentage of this phase relative to the overall start performance is 11% for men and 12% for women at 15 meters (Tor et al., 2014). For the 5-meter distance, this phase accounts for 46–56% (Matuš & Kandrác, 2020). This initial phase determines the flight phase and the subsequent phases. Optimising movement on the starting block and the kick start take-off have been the focus of several studies referenced in our review. These studies utilized various starting blocks or platforms, including Omega OSB11 (Matuš et al., 2024a, 2024c; Qui et al., 2021; Wardzyk et al., 2022), Omega OSB12 starting platform (Matuš et al., 2021a, 2021b; Matuš et al., 2020; Matuš et al., 2022; Matuš et al., 2024b; Matuš & Kandrác, 2020), Omega OSB14 (Rudnik et al., 2022; Rudnik et al., 2023), SEIKO starting block (Hyodo & Wada, 2023), SO2-X, Agle Timing (Djurkovic et al., 2019), and KiSwim (Burkhardt et al., 2020). All Omega starting blocks share the same surface treatment and kick plate (adjusted the kick plate to positions 1–5) and are commonly used at major events such as the Olympic Games. Starting blocks from other manufacturers or their models may differ in this aspect, which could potentially affect the resulting kinematic parameters in the block phase. However, no study has specifically addressed this issue.

The swimmer's initial set position may influence performance in the kick-start block phase. Variations in arm placement can shift the body's centre of mass. At the same time, the kick-plate setting can further modify the initial body configuration and joint angles, which together may affect block-phase mechanics. For descriptive purposes, we classify the set position on the starting block as front-, neutral-, and rear-weighted. Among junior swimmers, comparisons of these set positions revealed the most significant differences in block-phase kinematics between the front- and rear-weighted positions across all kick-plate settings. Moreover, the rear-weighted po-

sition combined with kick-plate settings 3–4 was associated with the fastest time to 5 m and characteristic set-position angles (FKA 131–133°, RKA 80–82°, trunk angle 40–43°) (Matuš et al., 2020; Matuš et al., 2021a; Matuš & Kandrác, 2020).

Junior swimmers achieved similar angular values in the basic position as male swimmers (Matuš et al., 2021b). The trunk angle at toe-off was correlated with starting performance for both elite male and female swimmers (Shepherd et al., 2023). Wardzyk et al. (2022) divided swimmers into two groups: fast swimmers (FS) and slow swimmers (SS). FS swimmers achieved a higher hip position at the start signal ($p > 0.05$, 1.56 ± 0.05 meters vs. 1.45 ± 0.05 meters). Other differences were observed in the entry angle ($23.89 \pm 6.50^\circ$ vs. $35.12 \pm 3.43^\circ$). From this perspective, competitive swimmers should focus on setting the kick plate, arm position, and increasing hip elevation in the initial position, which may help maximise horizontal take-off velocity.

In terms of time parameters in the block phase, block time ranged from 0.68–0.91 seconds in junior swimmers (Matuš et al., 2020; Matuš et al., 2020c; Matuš et al., 2021; Matuš et al., 2024a; Matuš et al., 2024b; Matuš & Kandrác, 2020; Wardzyk et al., 2022), 0.66–0.72 seconds in senior swimmers (Djurkovic et al., 2019; Matuš et al., 2024a, 2024b; Sánchez et al., 2021), and 0.59–0.72 seconds in elite swimmers (Rundik et al., 2022; Rudnik et al., 2023; Shepherd et al., 2023). Differences in swimmer performance can correspond to a 0.09-second difference in block time. Elite swimmers achieved a reaction time of 0.17–0.18 seconds (Rudnik et al., 2022). Burkhardt et al. (2020) identified high reliability ($ICC > 0.75$) for block time from the start to 15 meters. Djurkovic et al. (2019) reported a significant effect of block time ($t = 2.88$; $p = 0.010$) on 10 meters. Women showed longer block times ($p = 0.002$; $\eta^2 = 0.18$) and shorter reaction times than men (Matuš et al., 2021a; Matuš et al., 2021b; Matuš et al., 2024a, 2024c; Rudnik et al., 2022; Rudnik et al., 2023). Cicienia et al. (2020) observed differences in block time among elite swimmers ($F(2, 38) = 4.264$, $p = 0.026$). Block time was shorter when the kick plate distance was one shin's length versus $<$ shin length (0.691 ± 0.055 seconds vs 0.715 ± 0.056 seconds) and $>$ shin length (0.691 ± 0.055 seconds vs 0.698 ± 0.056 seconds, $p < 0.05$). The results of the aforementioned studies indicate that reaction time and block time depend on the starting position on the block, with junior and elite swimmers achieving shorter reaction times in a front-weighted position. In Rudnik et al. (2022), elite female swimmers had the shortest block time and reaction time when the kick plate was shifted one level back from their preferred position. Across stroke types, swimmers achieved shorter block times in freestyle than in breaststroke (Matuš et al., 2024a, 2024c). For the 50-meter and 100-meter breaststroke starts, high correlations ($r = 0.76–0.91$) were found between block time and final time for both genders (Sánchez et al., 2021).

Regarding the hands take-off, elite swimmers achieved shorter times in forward and backward positions one level from their preferred kick plate position, while hands take-off reaction time was the same for all kick plate positions. Elite female swimmers achieved the shortest times in the preferred position (Rudnik et al., 2022). In the study by Hyodo and

Wada (2023), the involvement of the upper limbs in body velocity during the start jump was evaluated. Swimmers who engaged their arms during the start jump from the starting block achieved significantly higher vertical velocities ($p > 0.05$) at a smaller take-off angle than in starts without arm involvement. This may affect the directional velocity.

Regarding the time characteristics of the lower limbs on the Omega OSB14 starting block, elite swimmers achieved the shortest rear-foot take-off and rear-foot take-off reaction times in the rear position of the kick plate, one level from the preferred position ($p > 0.05$). Conversely, in the front foot support, this was the slowest position ($p > 0.05$). Similar results were found for elite female swimmers. In this basic position, the shortest block movement time was measured (0.55 ± 0.05 seconds). Elite female swimmers had a more extended movement time by 0.05-0.06 seconds. Regardless of the kick plate position, swimmers achieved similar times on the starting block. The forward position of the kick plate delayed rear-foot take-off and shortened the duration of the front-foot stand (Rudnik et al., 2022). Elite swimmers achieved a take-off horizontal velocity of 4.37-4.58 m/s, a take-off vertical velocity of -0.61 m/s, and a final take-off velocity of 4.63 m/s. For elite junior swimmers, take-off parameters were lower (Qiu et al., 2021; Rudnik et al., 2023; Shepherd et al., 2023). Compared to women, men achieved higher take-off velocities ($p < 0.001$; $\eta^2 = 0.29$) (Rudnik et al., 2023). Shifting the kick plate one level forward from the preferred position reduced rear-foot take-off and shortened the front-foot stand. A kick plate position effect was observed for those variables, with larger effect sizes in males, whereas in females, a change of approximately two positions was required to achieve significance (Rudnik, 2022). Significant correlations ($p < 0.01$) were also found for elite junior female swimmers between take-off horizontal and vertical velocity (Qiu et al., 2021) and time to 5 meters. Take-off velocity was identified as a reliable kinematic parameter ($ICC > 0.75$) in the start to 15 meters (Burkhardt et al., 2020).

Other studies have explored lower-limb positioning in the basic position, such as strong front vs. back (Burkhardt et al., 2020), non-preferential vs. preferential (Matuš et al., 2021b), and wide vs. narrow (Matuš et al., 2024b). Burkhardt et al. (2020) recommend that swimmers (of varying performance levels, men and women together) place their stronger lower limb on the kick plate. On the other hand, Matuš et al. (2021b) highlight the importance of lower limb dominance and its placement on the OSB12 starting platform. For most tested female swimmers, the optimal basic position on the starting block was neutral- or rear-weighted, with the kick plate set to positions 3-4 and the right leg placed on the front edge of the OSB12 platform. In the study by Matuš et al. (2024b), wide vs narrow basic positions on the starting block revealed significant differences ($p < 0.05$) in block time (0.02 second), time to 2 meter (0.05 second), flight and glide time and distance, maximal depth, and time to 5 meter (0.08 s) in favor of the narrow position. They recommend that starting blocks or their platforms feature a central line to help swimmers better orient themselves and correctly position their feet in the basic starting position.

Flight phase

The flight phase can be characterised as the time from the last contact of the lower limbs with the starting block to the first contact with the water surface. At a distance of 15 meters, this phase accounts for 4% in men and 5% in women (Tor et al., 2014). For the 5-meter distance, the phase represents 19-22% (Matuš & Kandrác, 2020). When determining differences in the selected flight phase parameters among junior competitive swimmers, significant differences ($p < 0.05$) were found between the front-weighted start (kick plate in position 1) and other starts. The most extended flight phase (2.74-2.80 meters), ranging from 0.35 seconds to 0.37 seconds, was recorded when the takeoff angle was between 40° and 41° . The head distance from the water surface ranged from 1.33 meters to 1.38 meters, with subsequent water entry at 38° following the rear-weighted start with the kick plate in positions 3 and 4. These parameters resulted in the shortest times to 5 meters (Matuš & Kandrác, 2020). With a higher hip joint position in the basic position on the starting block, swimmers achieved a more extended flight phase by 0.12 meters in a shorter time of 0.07 seconds and a smaller takeoff angle of 11.23° and entry angle of 3.56° compared to swimmers with a lower position (Wardzyk et al., 2022). Regarding flight time and distance, junior swimmers achieved 0.27-0.41 seconds at 2.61-3.40 meters, seniors 0.31 seconds at 3.25-3.60 meters, and elite swimmers 0.29-0.34 seconds at 2.83 meters. For juniors, the takeoff angle ranged from 23° to 41° , and the entry angle was 36° to 39° , while elite swimmers had a takeoff angle of 34° and an entry angle of 37° (Matuš et al., 2021a; Matuš et al., 2022; Matuš et al., 2024a; Matuš et al., 2024c; Rudnik et al., 2022; Rudnik et al., 2023; Sánchez et al., 202; Shepherd et al., 2023; Wardzyk et al., 2022). Gender differences ($p < 0.01$) were observed in women, with a shorter flight phase ($p < 0.001$; $\eta^2 = 0.40$), as well as a shorter flight distance (Matuš et al., 2021b; Matuš et al., 2024a, 2024c; Rudnik et al., 2022; Rudnik et al., 2023). Among junior elite female swimmers, a significant correlation ($p < 0.05$) was found between the length of the flight phase, entry angle, and time to 5 meters (Qiu et al., 2021). Djurkovic et al. (2019) highlighted the impact of flight phase parameters on the final time to 10 meters: entry velocity ($t = -13.17$; $p = 0.000$), flight time ($t = 9.54$; $p = 0.000$), flight distance ($t = -2.67$; $p = 0.016$), and flight velocity ($t = 2.53$; $p = 0.021$). The differences observed during the flight phase are attributable to the swimmers' starting block position and performance levels. When comparing swimming styles, swimmers in freestyle and breaststroke exhibited similar flight-phase times. However, differences were observed in flight distance, with swimmers in breaststroke achieving up to 3.60 meters (Matuš et al., 2024a, 2024c).

Underwater phase

This is one of the longest phases of the start phases. The underwater phase can be characterised as the period from the swimmer's entry into the water until resurfacing to resume swimming. Overall, this phase accounts for 61% in men and 52% in women for the start-to-15-meter phase (Tor et al., 2014). The underwater phase can be divided into gliding and the first swimming movements, during which the swimmer

reaches the water's surface and begins swimming. For the first 5 meters, gliding contributes 30-33% to the final time (Matuš & Kandrác, 2020). In the 50-meter freestyle, the contribution was 42% for men and 41% for women. In the 50-meter breaststroke, the contribution was 54% for men and 49% for women, depending on the age category (Matuš et al., 2024a; Matuš et al., 2024c). Performance in this phase can also be influenced to some extent by performance in the previous phases (block and flight). In studies in which performance was monitored only at 5 meters, competitive swimmers exhibited only gliding without undulation (Matuš et al., 2020; Matuš et al., 2021a; Matuš et al., 2021b; Matuš et al., 2022; Matuš et al., 2024b; Matuš and Kandrác, 2020). In these studies, glide time ranged from 0.52 to 0.55 seconds, glide distance from 2.27 to 2.39 meters, and maximum depth from -0.89 to -0.92 meters. In the study by Wardzyk et al. (2022), a shorter glide time and distance were recorded with a deeper maximum depth (-1.05 to -1.11 meters). The authors point out that competitive swimmers with a higher hip position at the start signal had a shorter glide time by 0.05 seconds. The differences between the studies were attributable to methodological differences: in this study, swimmers performed starts up to 15 meters, whereas in the other study, they performed starts up to 5 meters. This means their glide distance and time were shorter, as the subsequent first kick, undulation, first arm movements, resurfacing, and swimming began. Elite junior female swimmers reached a smaller maximum depth of -0.73 meters, with the first kick occurring at a distance of 5.40 ± 0.48 meters (Qiu et al., 2021). Competitive junior female swimmers also reached a smaller maximum depth (Matuš et al., 2021). Djurkovic et al. (2019) highlighted the impact of underwater time on the final time to 10 meters ($t=66.09$; $p=0.000$). In freestyle for 50 meters, inter-sex differences were more evident in underwater time ($p<0.01$) than in underwater distance ($p<0.05$). Senior swimmers (both men and women) had a more extended underwater phase than juniors. Similarly, this was also the case in the breaststroke swimming style. A greater underwater distance was observed among swimmers in the 50-meter breaststroke discipline (Matuš et al., 2024a, 2024c), as this swimming style is not limited to 15 meters, unlike other swimming styles. In the study by Sánchez et al. (2021), during the 50-meter breaststroke start, senior swimmers achieved a shorter distance (12.50 ± 0.92 meters) than at the 100-meter breaststroke start (13.37 ± 1.28 meters). Women achieved approximately 1 meter shorter underwater distance. Regarding the time to 5 meters, junior swimmers achieved a shorter time when the rear support was at the 3rd or 4th level, with a neutral or rear-weighted position (Matuš et al., 2020; Matuš et al., 2021b, Matuš et al., 2024; Matuš and Kandrác, 2020), when the hip joint position was higher during the start signal (Wardzyk et al., 2022) and with a narrower basic position on the starting block (Matuš et al., 2024b). The key parameters determining performance to 5 meters during the above-water phase include rear knee angle, block time, take-off angle, and time to 2 meters (Matuš et al., 2021a).

Swim phase

The swim phase is the period following the underwater phase, extending from the moment the swimmer's head resur-

faces to the water's surface until the head reaches the 15-meter mark. The percentage contribution of this phase to the total time at 15 meters was 22% for men and 33% for women (Tor et al., 2014). In the 50-meter freestyle, the contribution was 44% for men and 47% for women. In the 50-meter breaststroke, the contribution was 35% for men and 41% for women, depending on the age category (Matuš et al., 2024a; Matuš et al., 2024c).

Regarding performance in the 15-meter start, senior (6.31-6.72 seconds) and elite (6.33-6.41 seconds) swimmers recorded shorter times than junior competitive swimmers (6.94-7.09 seconds) (Matuš et al., 2024c; Rudnik et al., 2022; Rudnik et al., 2023; Sánchez et al., 2021; Wardzyk et al., 2022). Women recorded times approximately 1 second slower (Qiu et al., 2021; Rudnik et al., 2022; Rudnik et al., 2023; Sánchez et al., 2021; Shepherd et al., 2023). The time between T5 - 10 meters was 2.35 seconds, and the time between T10 - 15 meters was 2.56 seconds. For women, the times were slightly longer (Rudnik et al., 2023). A shorter time to 15 meters was also influenced by the starting position on the block and the position of the rear support (Rudnik et al., 2022; Wardzyk et al., 2022).

This suggests that the acceleration gained during the underwater and above-water phases gradually decreases during the swim phase, as the swimmer transitions from the air to the water environment, with the swimmer achieving the greatest acceleration during the block phase. A significant correlation was found between variables describing overall starting performance (times to 5-meter, 10-meter, and 15-meter) and variables commonly identified as determinants of starting performance (block phase duration, take-off horizontal velocity, and flight distance) in male swimmers (Rudnik et al., 2023).

Practical implications

The present synthesis suggests that coaches and swimmers should prioritise start-phase elements that were most consistently linked to performance across studies. In practical terms, this includes the systematic individualisation of the set position (kick-plate setting, arm placement, and hip height) to improve take-off mechanics (particularly horizontal velocity) and to control entry characteristics that subsequently shape the underwater trajectory. Given the stroke-specific contribution of the underwater phase (notably in breaststroke), start optimisation should be aligned with the race demands and the swimmer's ability to maintain efficient underwater speed. Where possible, practitioners should use repeated trials and reliable kinematic indicators (e.g., block time, take-off velocity, flight distance) to monitor start changes over time rather than relying on a single trial.

Strengths

A key strength of this review is the phase-based organisation of the kick-start literature, which enables coaches and researchers to interpret findings within a coherent performance framework (block, flight, underwater, swim). By summarising evidence across different populations (junior, senior, elite; male and female) and stroke contexts, the review provides an applied overview of which kinematic parameters

most consistently relate to start performance and which appear more dependent on protocol and equipment.

Limitations and future directions

The conclusions of this review should be interpreted in light of methodological heterogeneity across studies, including differences in tested distances (e.g., 5 m vs. 15 m), phase definitions, measurement systems, sample sizes, and starting block/platform models. This limits direct quantitative comparability and may partially explain conflicting results for some parameters. In addition to methodological heterogeneity, the overall quality and potential risk of bias of the included studies should also be considered when interpreting the present findings. The included studies were of good to fair methodological quality with a generally low to moderate risk of bias. The most common limitations were small sample sizes, lack of sample size justification, and limited reporting of assessor blinding, which are typical in biomechanical studies of elite athletes. Future research should aim to standardise reporting (clear phase definitions and consistent outcome metrics), directly compare starting block models and kick-plate configurations under controlled conditions, and include more stroke-specific and sex-specific analyses. Longitudinal/intervention designs are also needed to determine whether targeted changes in start mechanics translate into meaningful improvements in competition performance.

Conclusion

The results of the studies included in this review highlight differences across the block, flight, underwater, and swim phases with respect to sex, stroke type, and performance. The reviewed evidence suggests that several technique modifications can optimise the kick start: a kick-plate setting at level 3 or 4; a narrow stance with a neutral- or rear-weighted set position; and a higher hip position at the start signal, tailored to sex, stroke, and performance level. Collectively, these adjustments were associated with improvements in above-water and underwater execution, resulting in shorter times to 5 m, 10 m, and 15 m. Overall, the most consistent performance benefits across studies appear to come from optimising the set position and take-off mechanics to support an effective entry and a faster underwater transition. Therefore, the start optimisation should primarily target the block-to-entry sequence and the quality of the underwater phase, as these elements most directly translate into faster early-race performance. Insights into the kick-start technique should assist coaches and swimmers in achieving a more effective kick start, which is commonly used in elite swimming competitions.

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Conflict of Interest

The authors declare that there is no conflict of interest.

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SM only publishes studies that have been approved by an institutional ethics committee (when a study involves humans or animals). Fail to provide such information prevent its publication. To ensure these requirements, it is essential that submission documentation is complete. If you have not completed this step yet, go to SM website and fill out the two required documents: Declaration of Potential Conflict of Interest and Authorship Statement. Whether or not your study uses humans or animals, these documents must be completed and signed by all authors and attached as supplementary files in the originally submitted manuscript.

1.6. After Acceptance

After the manuscript has been accepted, authors will receive a PDF version of the manuscripts for authorization, as it should look in printed version of SM. Authors should carefully check for omissions. Reporting errors after this point will not be possible and the Editorial Board will not be eligible for them.

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2. MANUSCRIPT STRUCTURE

2.1. Title Page

The first page of the manuscripts should be the title page, containing: title, type of publication, running head, authors, affiliations, corresponding author, and manuscript information. *See example:*

Body Composition of Elite Soccer Players from Montenegro

Original Scientific Paper

Elite Soccer Players from Montenegro

Dusko Bjelica¹

¹Univeristy of Montenegro, Faculty for Sport an Physical Education, Niksic, Montenegro

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University of Montenegro

Faculty for Sport and Physical Education

Narodne omladine bb, 81400 Niksic, Montenegro

E-mail: sportmont@t-com.me

Word count: 2,946

Abstract word count: 236

Number of Tables: 3

Number of Figures: 0

2.1.1. Title

Title should be short and informative and the recommended length is no more than 20 words. The title should be in Title Case, written in uppercase and lowercase letters (initial uppercase for all words except articles, conjunctions, short prepositions no longer than four letters etc.) so that first letters of the words in the title are capitalized. Exceptions are words like: “and”, “or”, “between” etc. The word following a colon (:) or a hyphen (-) in the title is always capitalized.

2.1.2. Type of publication

Authors should suggest the type of their submission.

2.1.3. Running head

Short running title should not exceed 50 characters including spaces.

2.1.4. Authors

The form of an author’s name is first name, middle initial(s), and last name. In one line list all authors with full names separated by a comma (and space). Avoid any abbreviations of academic or professional titles. If authors belong to different institutions, following a family name of the author there should be a number in superscript designating affiliation.

2.1.5. Affiliations

Affiliation consists of the name of an institution, department, city, country/territory (in this order) to which the author(s) belong and to which the presented / submitted work should be attributed. List all affiliations (each in a separate line) in the order corresponding to the list of authors. Affiliations must be written in English, so carefully check the official English translation of the names of institutions and departments.

Only if there is more than one affiliation, should a number be given to each affiliation in order of appearance. This number

should be written in superscript at the beginning of the line, separated from corresponding affiliation with a space. This number should also be put after corresponding name of the author, in superscript with no space in between.

If an author belongs to more than one institution, all corresponding superscript digits, separated with a comma with no space in between, should be present behind the family name of this author.

In case all authors belong to the same institution affiliation numbering is not needed.

Whenever possible expand your authors' affiliations with departments, or some other, specific and lower levels of organization.

2.1.6. Corresponding author

Corresponding author's name with full postal address in English and e-mail address should appear, after the affiliations. It is preferred that submitted address is institutional and not private. Corresponding author's name should include only initials of the first and middle names separated by a full stop (and a space) and the last name. Postal address should be written in the following line in sentence case. Parts of the address should be separated by a comma instead of a line break. E-mail (if possible) should be placed in the line following the postal address. Author should clearly state whether or not the e-mail should be published.

2.1.7. Manuscript information

All authors are required to provide word count (excluding title page, abstract, tables/figures, figure legends, Acknowledgements, Conflict of Interest, and References), the Abstract word count, the number of Tables, and the number of Figures.

2.2. Abstract

The second page of the manuscripts should be the abstract and key words. It should be placed on second page of the manuscripts after the standard title written in upper and lower case letters, bold.

Since abstract is independent part of your paper, all abbreviations used in the abstract should also be explained in it. If an abbreviation is used, the term should always be first written in full with the abbreviation in parentheses immediately after it. Abstract should not have any special headings (e.g., Aim, Results...).

Authors should provide up to six key words that capture the main topics of the article. Terms from the Medical Subject Headings (MeSH) list of Index Medicus are recommended to be used.

Key words should be placed on the second page of the manuscript right below the abstract, written in italic. Separate each key word by a comma (and a space). Do not put a full stop after the last key word. *See example:*

Abstract

Results of the analysis of

Key words: *spatial memory, blind, transfer of learning, feedback*

2.3. Main Chapters

Starting from the third page of the manuscripts, it should be the main chapters. Depending on the type of publication main manuscript chapters may vary. The general outline is: Introduction, Methods, Results, Discussion, Acknowledgements (optional), Conflict of Interest (optional). However, this scheme may not be suitable for reviews or publications from some areas and authors should then adjust their chapters accordingly but use the general outline as much as possible.

2.3.1. Headings

Main chapter headings: written in bold and in Title Case. *See example:*

✓ Methods

Sub-headings: written in italic and in normal sentence case. Do not put a full stop or any other sign at the end of the title.

Do not create more than one level of sub-heading. *See example:*

✓ *Table position of the research football team*

2.3.2 Ethics

When reporting experiments on human subjects, there must be a declaration of Ethics compliance. Inclusion of a statement

such as follow in Methods section will be understood by the Editor as authors' affirmation of compliance: "This study was approved in advance by [name of committee and/or its institutional sponsor]. Each participant voluntarily provided written informed consent before participating." Authors that fail to submit an Ethics statement will be asked to resubmit the manuscripts, which may delay publication.

2.3.3 Statistics reporting

SM encourages authors to report precise p-values. When possible, quantify findings and present them with appropriate indicators of measurement error or uncertainty (such as confidence intervals). Use normal text (i.e., non-capitalized, nonitalic) for statistical term "p".

2.3.4. 'Acknowledgements' and 'Conflict of Interest' (optional)

All contributors who do not meet the criteria for authorship should be listed in the 'Acknowledgements' section. If applicable, in 'Conflict of Interest' section, authors must clearly disclose any grants, financial or material supports, or any sort of technical assistances from an institution, organization, group or an individual that might be perceived as leading to a conflict of interest.

2.4. References

References should be placed on a new page after the standard title written in upper and lower case letters, bold.

All information needed for each type of must be present as specified in guidelines. Authors are solely responsible for accuracy of each reference. Use authoritative source for information such as Web of Science, Medline, or PubMed to check the validity of citations.

2.4.1. References style

SM adheres to the American Psychological Association 6th Edition reference style. Check "American Psychological Association. (2009). Concise rules of APA style. American Psychological Association." to ensure the manuscripts conform to this reference style. Authors using EndNote® to organize the references must convert the citations and bibliography to plain text before submission.

2.4.2. Examples for Reference citations

One work by one author

- ✓ In one study (Reilly, 1997), soccer players
- ✓ In the study by Reilly (1997), soccer players
- ✓ In 1997, Reilly's study of soccer players

Works by two authors

- ✓ Duffield and Marino (2007) studied
- ✓ In one study (Duffield & Marino, 2007), soccer players
- ✓ In 2007, Duffield and Marino's study of soccer players

Works by three to five authors: cite all the author names the first time the reference occurs and then subsequently include only the first author followed by et al.

- ✓ First citation: Bangsbo, Iaia, and Krstrup (2008) stated that
- ✓ Subsequent citation: Bangsbo et al. (2008) stated that

Works by six or more authors: cite only the name of the first author followed by et al. and the year

- ✓ Krstrup et al. (2003) studied
- ✓ In one study (Krstrup et al., 2003), soccer players

Two or more works in the same parenthetical citation: Citation of two or more works in the same parentheses should be listed in the order they appear in the reference list (i.e., alphabetically, then chronologically)

- ✓ Several studies (Bangsbo et al., 2008; Duffield & Marino, 2007; Reilly, 1997) suggest that

2.4.3. Examples for Reference list

Journal article (print):

Nepocatyč, S., Balilionis, G., & O'Neal, E. K. (2017). Analysis of dietary intake and body composition of female athletes over a competitive season. *Montenegrin Journal of Sports Science and Medicine*, 6(2), 57-65. doi: 10.26773/mjssm.2017.09.008

Duffield, R., & Marino, F. E. (2007). Effects of pre-cooling procedures on intermittent-sprint exercise performance in warm conditions. *European Journal of Applied Physiology*, 100(6), 727-735. doi: 10.1007/s00421-007-0468-x

Krustrup, P., Mohr, M., Amstrup, T., Rysgaard, T., Johansen, J., Steensberg, A., Bangsbo, J. (2003). The yo-yo intermittent recovery test: physiological response, reliability, and validity. *Medicine and Science in Sports and Exercise*, 35(4), 697-705. doi: 10.1249/01.MSS.0000058441.94520.32

Journal article (online; electronic version of print source):

Williams, R. (2016). Krishna's Neglected Responsibilities: Religious devotion and social critique in eighteenth-century North India [Electronic version]. *Modern Asian Studies*, 50(5), 1403-1440. doi:10.1017/S0026749X14000444

Journal article (online; electronic only):

Chantavanich, S. (2003, October). Recent research on human trafficking. *Kyoto Review of Southeast Asia*, 4. Retrieved November 15, 2005, from <http://kyotoreview.cseas.kyoto-u.ac.jp/issue/issue3/index.html>

Conference paper:

Pasadilla, G. O., & Milo, M. (2005, June 27). *Effect of liberalization on banking competition*. Paper presented at the conference on Policies to Strengthen Productivity in the Philippines, Manila, Philippines. Retrieved August 23, 2006, from <http://siteresources.worldbank.org/INTPHILIPPINES/Resources/Pasadilla.pdf>

Encyclopedia entry (print, with author):

Pittau, J. (1983). Meiji constitution. In *Kodansha encyclopedia of Japan* (Vol. 2, pp. 1-3). Tokyo: Kodansha.

Encyclopedia entry (online, no author):

Ethnology. (2005, July). In *The Columbia encyclopedia* (6th ed.). New York: Columbia University Press. Retrieved November 21, 2005, from <http://www.bartleby.com/65/et/ethnolog.html>

Thesis and dissertation:

Pyun, D. Y. (2006). *The proposed model of attitude toward advertising through sport*. Unpublished Doctoral Dissertation. Tallahassee, FL: The Florida State University.

Book:

Borg, G. (1998). *Borg's perceived exertion and pain scales*: Human kinetics.

Chapter of a book:

Kellmann, M. (2012). Chapter 31-Overtraining and recovery: Chapter taken from *Routledge Handbook of Applied Sport Psychology* ISBN: 978-0-203-85104-3 *Routledge Online Studies on the Olympic and Paralympic Games* (Vol. 1, pp. 292-302).

Reference to an internet source:

Agency. (2007). Water for Health: Hydration Best Practice Toolkit for Hospitals and Healthcare. Retrieved 10/29, 2013, from www.rcn.org.uk/newsevents/hydration

2.5. Tables

All tables should be included in the main manuscript file, each on a separate page right after the Reference section.

Tables should be presented as standard MS Word tables.

Number (Arabic) tables consecutively in the order of their first citation in the text.

Tables and table headings should be completely intelligible without reference to the text. Give each column a short or abbreviated heading. Authors should place explanatory matter in footnotes, not in the heading. All abbreviations appearing in a table and not considered standard must be explained in a footnote of that table. Avoid any shading or coloring in your tables and be sure that each table is cited in the text.

If you use data from another published or unpublished source, it is the authors' responsibility to obtain permission and acknowledge them fully.

2.5.1. Table heading

Table heading should be written above the table, in Title Case, and without a full stop at the end of the heading. Do not use suffix letters (e.g., Table 1a, 1b, 1c); instead, combine the related tables. See example:

✓ **Table 1.** Repeated Sprint Time Following Ingestion of Carbohydrate-Electrolyte Beverage

2.5.2. Table sub-heading

All text appearing in tables should be written beginning only with first letter of the first word in all capitals, i.e., all words for variable names, column headings etc. in tables should start with the first letter in all capitals. Avoid any formatting (e.g., bold, italic, underline) in tables.

2.5.3. Table footnotes

Table footnotes should be written below the table.

General notes explain, qualify or provide information about the table as a whole. Put explanations of abbreviations, symbols, etc. here. General notes are designated by the word *Note* (italicized) followed by a period.

- ✓ *Note*. CI: confidence interval; Con: control group; CE: carbohydrate-electrolyte group.

Specific notes explain, qualify or provide information about a particular column, row, or individual entry. To indicate specific notes, use superscript lowercase letters (e.g. ^{a,b,c}), and order the superscripts from left to right, top to bottom. Each table's first footnote must be the superscript ^a.

- ✓ ^aOne participant was diagnosed with heat illness and n = 19,^bn = 20.

Probability notes provide the reader with the results of the tests for statistical significance. Probability notes must be indicated with consecutive use of the following symbols: * † ‡ § ¶ || etc.

- ✓ *P<0.05, †p<0.01.

2.5.4. Table citation

In the text, tables should be cited as full words. *See example:*

- ✓ Table 1 (first letter in all capitals and no full stop)
- ✓ ...as shown in Tables 1 and 3. (citing more tables at once)
- ✓ ...result has shown (Tables 1-3) that... (citing more tables at once)
- ✓ ...in our results (Tables 1, 2 and 5)... (citing more tables at once)

2.6. Figures

On the last separate page of the main manuscript file, authors should place the legends of all the figures submitted separately.

All graphic materials should be of sufficient quality for print with a minimum resolution of 600 dpi. SM prefers TIFF, EPS and PNG formats.

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Figures and figure legends should be completely intelligible without reference to the text.

The price of printing in color is 50 EUR per page as printed in an issue of SM.

2.6.1. Figure legends

Figures should not contain footnotes. All information, including explanations of abbreviations must be present in figure legends. Figure legends should be written below the figure, in sentence case. *See example:*

- ✓ Figure 1. Changes in accuracy of instep football kick measured before and after fatigued. SR – resting state, SF – state of fatigue, *p>0.01, †p>0.05.

2.6.2. Figure citation

All graphic materials should be referred to as Figures in the text. Figures are cited in the text as full words. *See example:*

- ✓ Figure 1
- × figure 1
- × Figure 1.
- ✓ ...exhibit greater variance than the year before (Figure 2). Therefore...
- ✓ ...as shown in Figures 1 and 3. (citing more figures at once)
- ✓ ...result has shown (Figures 1-3) that... (citing more figures at once)

- ✓ ...in our results (Figures 1, 2 and 5)... (citing more figures at once)

2.6.3. Sub-figures

If there is a figure divided in several sub-figures, each sub-figure should be marked with a small letter, starting with a, b, c etc. The letter should be marked for each subfigure in a logical and consistent way. *See example:*

- ✓ Figure 1a
- ✓ ...in Figures 1a and b we can...
- ✓ ...data represent (Figures 1a-d)...

2.7. Scientific Terminology

All units of measures should conform to the International System of Units (SI).

Measurements of length, height, weight, and volume should be reported in metric units (meter, kilogram, or liter) or their decimal multiples.

Decimal places in English language are separated with a full stop and not with a comma. Thousands are separated with a comma.

Percentage Degrees	All other units of measure	Ratios	Decimal numbers	
✓ 10%	✓ 10°	✓ 10 kg	✓ 12:2	✓ 0.056
× 10 %	× 10 °	× 10kg	× 12 : 2	× .056

Signs should be placed immediately preceding the relevant number.

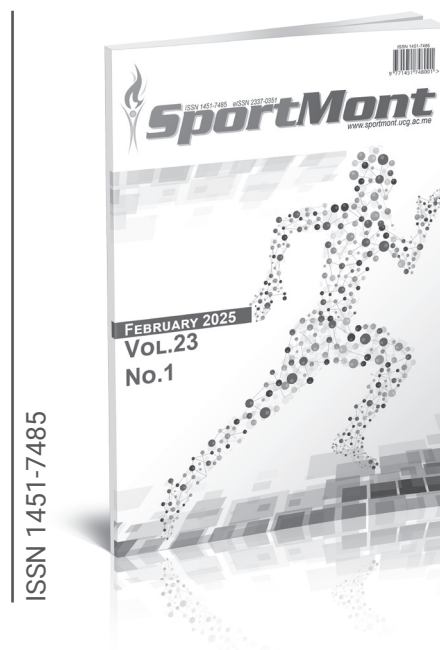
✓ 45±3.4	✓ p<0.01	✓ males >30 years of age
× 45 ± 3.4	× p < 0.01	× males > 30 years of age

2.8. Latin Names

Latin names of species, families etc. should be written in italics (even in titles). If you mention Latin names in your abstract they should be written in non-italic since the rest of the text in abstract is in italic. The first time the name of a species appears in the text both genus and species must be present; later on in the text it is possible to use genus abbreviations. *See example:*

- ✓ First time appearing: *musculus biceps brachii*

Abbreviated: *m. biceps brachii*



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SMJ is published three times a year, in February, June and October of each year. SMJ publishes original scientific papers, review papers, editorials, short reports, peer review - fair review, as well as invited papers and award papers in the fields of Sports Science and Medicine, as well as it can function as an open discussion forum on significant issues of current interest.

SMJ covers all aspects of sports science and medicine; all clinical aspects of exercise, health, and sport; exercise physiology and biophysical investigation of sports performance; sport biomechanics; sports nutrition; rehabilitation, physiotherapy; sports psychology; sport pedagogy, sport history, sport philosophy, sport sociology, sport management; and all aspects of scientific support of the sports coaches from the natural, social and humanistic side.

Prospective authors should submit manuscripts for consideration in Microsoft Word-compatible format. For more complete descriptions and submission instructions, please access the Guidelines for Authors pages at the SMJ website: <http://www.sportmont.me/?sekcija=page&p=51>. Contributors are urged to read SMJ's guidelines for the authors carefully before submitting manuscripts. Manuscripts submissions should be sent in electronic format to sportmont@ucg.ac.me or contact following Editors:

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Winter issue – February 2027



MONTENEGRIN JOURNAL OF SPORTS SCIENCE AND MEDICINE



CALL FOR CONTRIBUTIONS

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Prospective authors should submit manuscripts for consideration in Microsoft Word-compatible format. For more complete descriptions and submission instructions, please access the Guidelines for Authors pages at the MJSSM website: <http://www.mjssm.me/?sekcija=page&p=51>. Contributors are urged to read MJSSM's guidelines for the authors carefully before submitting manuscripts. Manuscripts submissions should be sent in electronic format to office@mjssm.me or contact following Editors:

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Damir SEKULIC, Editor-in Chief – damirsekulic.mjssm@gmail.com

Publication date: Spring issue – March 2026
Autumn issue – September 2026



MONTENEGRIN SPORTS ACADEMY

Founded in 2003 in Podgorica (Montenegro), the Montenegrin Sports Academy (MSA) is a sports scientific society dedicated to the collection, generation and dissemination of scientific knowledge at the Montenegrin level and beyond.

The Montenegrin Sports Academy (MSA) is the leading association of sports scientists at the Montenegrin level, which maintains extensive co-operation with the corresponding associations from abroad. The purpose of the MSA is the promotion of science and research, with special attention to sports science across Montenegro and beyond. Its topics include motivation, attitudes, values and responses, adaptation, performance and health aspects of people engaged in physical activity and the relation of physical activity and lifestyle to health, prevention and aging. These topics are investigated on an interdisciplinary basis and they bring together scientists from all areas of sports science, such as adapted physical activity, biochemistry, biomechanics, chronic disease and exercise, coaching and performance, doping, education, engineering

and technology, environmental physiology, ethics, exercise and health, exercise, lifestyle and fitness, gender in sports, growth and development, human performance and aging, management and sports law, molecular biology and genetics, motor control and learning, muscle mechanics and neuromuscular control, muscle metabolism and hemodynamics, nutrition and exercise, overtraining, physiology, physiotherapy, rehabilitation, sports history, sports medicine, sports pedagogy, sports philosophy, sports psychology, sports sociology, training and testing.

The MSA is a non-profit organization. It supports Montenegrin institutions, such as the Ministry of Education and Sports, the Ministry of Science and the Montenegrin Olympic Committee, by offering scientific advice and assistance for carrying out coordinated national and European research projects defined by these bodies. In addition, the MSA serves as the most important Montenegrin and regional network of sports scientists from all relevant subdisciplines.

The main scientific event organized by the Montenegrin Sports Academy (MSA) is the annual conference held in the first week of April.

Annual conferences have been organized since the inauguration of the MSA in 2003. Today the MSA conference ranks among the leading sports scientific congresses in the Western Balkans. The conference comprises a range of invited lecturers, oral and poster presentations from multi- and mono-disciplinary areas, as well as various types of workshops. The MSA conference is attended by national, regional and international sports scientists with academic careers. The MSA conference now welcomes up to 200 participants from all over the world.

It is our great pleasure to announce the upcoming 24th Annual Scientific Conference of Montenegrin Sports Academy "Sport, Physical Activity and Health: Contemporary Perspectives" to be held in Dubrovnik, Croatia, from 3 to 6 April, 2025. It is planned to be once again organized by the Montenegrin Sports Academy, in cooperation with the Faculty of Sport and Physical Education, University of Montenegro and other international partner institutions (specified in the partner section).

The conference is focused on very current topics from all areas of sports science and sports medicine including physiology and sports medicine, social sciences and humanities, biomechanics and neuromuscular (see Abstract Submission page for more information).

We do believe that the topics offered to our conference participants will serve as a useful forum for the presentation of the latest research, as well as both for the theoretical and applied insight into the field of sports science and sports medicine disciplines.





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