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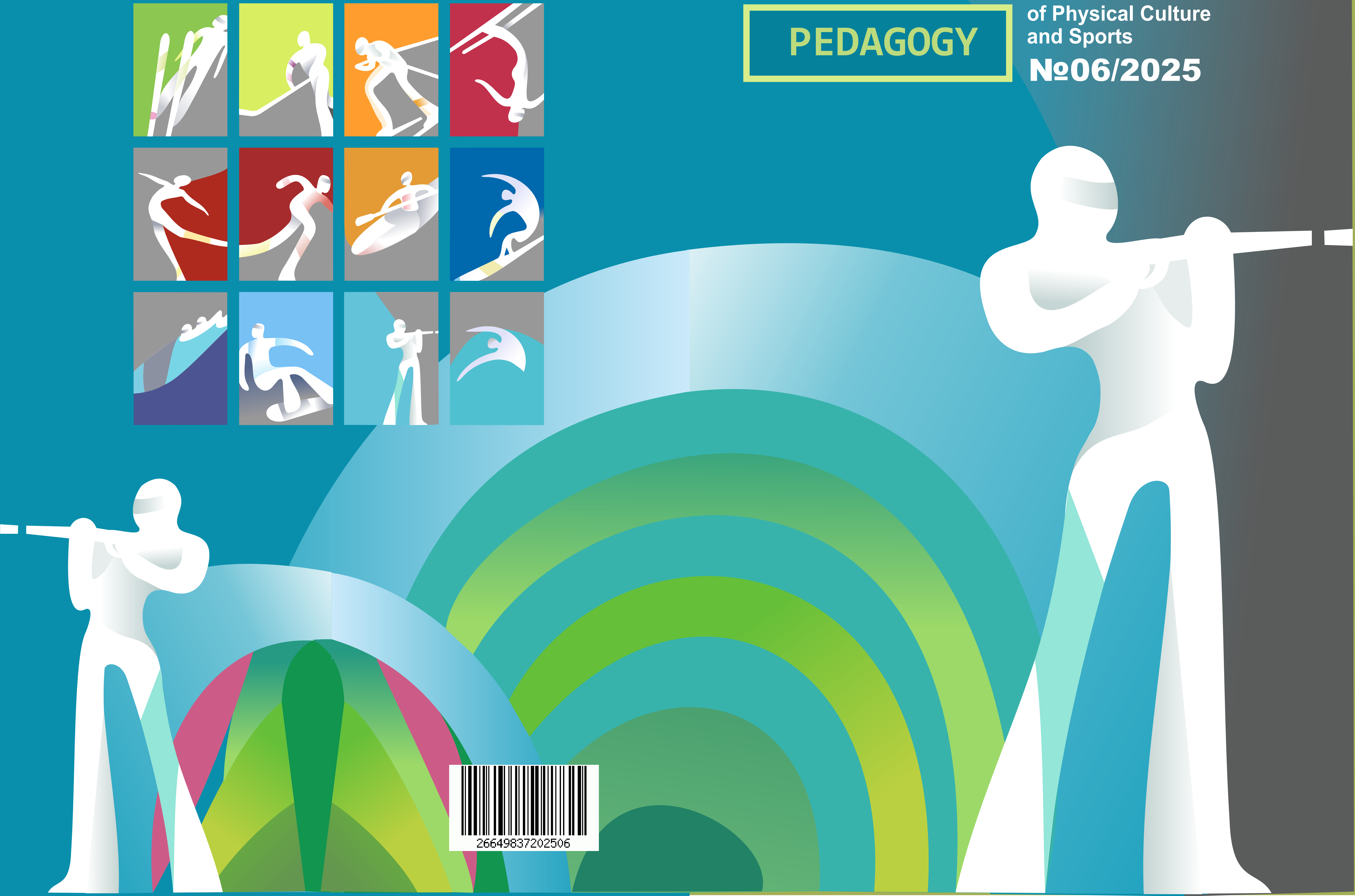

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CONTENTS

ORIGINAL ARTICLE

Efficacy of integrated neuromuscular training intervention on concurrent reduction of anterior cruciate ligament and hamstring injury risks in adolescent footballers

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

Abstract

Background and Study Aim Football is a physically demanding sport with a high risk of injuries, particularly anterior cruciate ligament (ACL) and hamstring strain injuries (HSIs). These injuries often lead to re-injury, prolonged rehabilitation, and reduced career longevity. Although various preventive strategies are applied, their relative effectiveness in reducing such risks among adolescent male footballers remains a matter of practical concern. This study aimed to determine the effects of integrated neuromuscular training on key injury-related risk factors.

Material and Methods Sixty-eight male adolescent footballers aged 16–18 years from two academies in Lakki Marwat were recruited for the study. Sixty-two participants completed the intervention, while six withdrew for personal reasons. The intervention group (n = 31) followed an eight-week INT program, consisting of four sessions per week, each lasting 80–90 minutes. The control group (n = 31) continued their routine football training. Pre- and post-test assessments were conducted to evaluate the effects of INT on the dependent variables. The Tuck Jump Assessment (TJA) was used to analyze landing biomechanics, a key risk factor for ACL injury. Isokinetic dynamometry was used to assess hamstring strength and calculate the conventional (Hcon:Qcon) and functional (Hexc:Qcon) hamstring-to-quadriceps ratios. The Active Knee Extension (AKE) test was used to assess hamstring flexibility.

Results The most significant result in the INT group was a 51% reduction in the TJA score, supported by a large effect size (d = 2.41). Overall, large effect sizes (d = 1.56–1.73) confirmed the intervention's potential effectiveness, as the INT group showed significant improvements from pre- to post-test in all tested variables.

Conclusions Significant positive changes were observed in TJA scores, indicating improved landing mechanics and a lower risk of ACL injury. Additionally, the intervention group demonstrated significant improvements in muscle peak torque, Hcon:Qcon ratio, Hexc:Qcon ratio, and AKE range of motion. These findings confirm that INT can simultaneously reduce key risk factors related to both movement mechanics and muscle strength for ACL and HSIs in adolescent male footballers.

Keywords: exertion, fitness, limitations, strenuous, rehabilitation

Introduction

In modern competitive football, adolescent players are exposed to intensive physical demands that challenge the musculoskeletal and neuromotor systems. Movements such as sprinting, cutting, jumping, and tackling place considerable stress on the lower extremities, increasing vulnerability to injury. Among the most prevalent and impactful are anterior cruciate ligament (ACL) ruptures and hamstring strain injuries (HSIs), both of which can result in significant functional impairment, extended rehabilitation periods, and reduced athletic longevity. The complexity of these injuries lies in their multifactorial origins, involving biomechanics, neuromuscular control, strength imbalances, and fatigue.

In this context, football is the world's most popular and widely played sport, with an estimated 3.5 billion spectators and over 250 million registered players in more than 200 member nations of the Fédération Internationale de Football Association (FIFA) [1]. Its popularity continues to rise among adolescents, who represent the most active and critical developmental age group in organized sport [2]. The game combines intense physical exertion, technical skill, rapid directional changes, dribbling,

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sprinting, and jumping [3]. These strenuous biomechanical activities place heavy demands on the lower limbs and make players, particularly adolescents, vulnerable to musculoskeletal injuries such as ACL ruptures and HSIs [4].

Based on the frequency of incidents and the long-term impact on physical fitness, ACL and hamstring injuries have a severe functional effect on players' overall performance [5]. Reducing the occurrence of these injuries through evidence-based preventive strategies is a key priority in football medicine [6]. Among these, anterior cruciate ligament (ACL) injury during adolescence is considered one of the most severe and functionally limiting [7]. From a physiological perspective, the ACL plays a central role in stabilizing the knee joint, particularly in rotational control [8]. This injury typically occurs during non-contact actions such as sudden changes of direction, dribbling, tackling, sprinting, or jumping [9].

ACL injury often requires surgical intervention followed by a lengthy rehabilitation period lasting from nine to twelve months [10]. In addition to the physical pain and emotional stress, players usually miss an entire season [11]. Even after returning to sport, adolescents face a high re-injury risk, with recurrence rates reported between 15% and 20% [12]. Furthermore, Wang et al. [13] confirmed that post-traumatic osteoarthritis is a long-term complication of ACL injury. This condition is frequently accompanied by chronic lower-limb pain and functional limitations that interfere with routine physical activities [14].

Hamstring strain injuries (HSIs) have also shown a significant increase in recent years. Ekstrand et al. [15] reported that hamstring tears account for 24% of all injuries among professional football players. Although HSIs are often perceived as less severe than ACL injuries, they have a re-injury rate exceeding 30%, which is notably high [16]. These injuries have multidimensional consequences, including psychological, physical, social, financial, and professional impacts. Athletes often experience fear of re-injury, depression, and emotional deprivation, which are frequently overlooked in clinical management [17]. Disruption of training, prolonged treatment, high rehabilitation costs, and the risk of recurrence are shared consequences of both ACL and hamstring injuries [18].

From a physiological perspective, the development of these injuries involves a complex interplay of physical, biomechanical, hormonal, and neuromuscular factors. Female athletes are at higher risk of ACL injuries than males, due to a combination of hormonal fluctuations, anatomical differences, and neuromuscular control patterns. Targeted training can mitigate many of the contributing factors. The most widely recognized risk factors for ACL injuries include dynamic knee valgus, quadriceps dominance, poor neuromuscular control, and limb asymmetry [19]. In the case of hamstring strains, one of the primary modifiable risk factors is insufficient eccentric hamstring strength, which plays a critical role in controlling leg swing during sprinting. If hamstring strength is inadequate, excessive strain may occur, leading to tissue damage [20]. Other contributing factors include poor hamstring flexibility and fatigue, which, under high-intensity conditions, can act synergistically to increase injury risk.

Several previous attempts have been made to address the issue of hamstring injuries in football players [21]. Among the most effective approaches is the Nordic Hamstring Exercise (NHE), which has shown consistent success in multiple meta-analyses [22]. The NHE enhances eccentric hamstring strength and significantly reduces the risk of HSIs. Similarly, for reducing risk factors associated with ACL injuries, structured prevention programs such as Prevent Injury and Enhance Performance (PEP) and FIFA 11+ have demonstrated efficacy in improving biomechanics and lowering injury incidence [23]. Despite the availability of such interventions, adolescent football players often remain vulnerable to injuries, including ACL tears and HSIs, due to limited time allocated for comprehensive neuromuscular training.

The current context underscores the relevance of investigating integrated neuromuscular training (INT) as a comprehensive preventive approach [24]. INT targets the simultaneous development of multiple athletic attributes, including muscular strength, power, flexibility, balance, agility, and coordination, within a sport-specific framework. It is designed to address both health- and skill-related components of athletic performance. Through structured progression, the INT program incorporates strength training, plyometrics, eccentric control, and balance exercises to improve core stability, dynamic postural control, and movement efficiency [25].

The primary focus of INT lies in the integrated functioning of the neuromuscular system, which underpins coordinated and adaptive performance across several physiological domains. Enhancing the stretch-shortening cycle, dynamic core stability, and hamstring control is essential for ACL injury prevention—components effectively addressed through plyometric training. Similarly, exercises involving single-leg balance contribute to improved knee joint stability and hamstring function. Overall, the INT program offers a multifaceted strategy for reducing the risk of sports-related injuries in adolescent athletes.

The FIFA 11+ program is a widely recognized neuromuscular training protocol designed to reduce injury risk. However, its primary focus is on general injury prevention, with limited emphasis on specific strength parameters such as the functional hamstring-to-quadriceps (H:Q) ratio. Naik [26] has further argued that, while FIFA 11+ is effective, its use as a standalone intervention may not sufficiently address the biomechanical risk factors for ACL injuries. Supporting the rationale for the present study, Owoeye et al. [27] emphasized the need for interventions that target multiple injury mechanisms simultaneously in football players.

This research addresses several critical gaps identified in the literature. One of the major gaps stems from socio-economic disparities. Most existing research on integrated neuromuscular training has been conducted in high-income settings with well-established sports infrastructure and access to expert coaching [28]. In contrast, regions such as Pakistan—and more specifically, the under-resourced city of Lakki Marwat in Khyber Pakhtunkhwa—lack the facilities, training standards, and funding typically found in developed countries. These differences in infrastructure, athlete preparation, and socio-economic conditions limit the generalizability of findings from wealthier contexts [29].

Another gap is the absence of context-specific research that focuses on the risk factors, prevalence, and prevention of ACL and hamstring injuries among adolescent football players. The current INT program seeks to bridge this gap by simultaneously targeting ACL-related movement mechanics and HSIs through the enhancement of eccentric hamstring strength. Addressing both mechanisms within a single intervention is a central aim of this study. Finally, there remains a broader need to design adaptable, context-sensitive training programs composed of evidence-based components that can be applied across diverse athletic populations [30].

Analysis of research findings has shown that neuromuscular training programs such as FIFA 11+, PEP, and the Nordic Hamstring Exercise can reduce specific injury risks in football players. Researchers emphasize that targeted improvements in movement mechanics, eccentric strength, and dynamic stability are essential for effective injury prevention, particularly among adolescents. At the same time, the practical implementation of these programs in low-resource settings remains challenging due to infrastructural limitations, limited training time, and contextual mismatch. This ongoing gap continues to hinder the development of accessible and comprehensive solutions capable of simultaneously addressing the complex injury risks faced by adolescent football players.

This study aimed to determine the effects of integrated neuromuscular training on key injury-related risk factors. It was hypothesized that adolescent football players who completed the INT intervention would demonstrate significantly greater improvements in modifiable risk indicators for anterior cruciate ligament and hamstring injuries compared to those in the control group.

Materials and Methods

Participants

The study involved 68 male adolescent football players aged 16 to 18 years, recruited from two established football academies in Lakki Marwat. Inclusion criteria were as follows: (a) a minimum of two years of active football experience, (b) no history of musculoskeletal injury in the past six months, and (c) no participation in any structured training program. Exclusion criteria included: (a) any musculoskeletal injury within the past six months, (b) a documented history of major orthopedic surgery, and (c) current use of regular medication. All participants provided informed consent, and the study protocol was approved by the Ethics Committee of the Department of Sports Sciences and Physical Education, Faculty of Allied Health Sciences, The University of Lahore (approval code: DSSPE/ECA/2025-135).

Study Design

A pre- and post-intervention experimental research design was employed in the present study. Before pre-test measurements, baseline health and fitness assessments were conducted. Participants were then randomly assigned to either the intervention group (INT; n = 34) or the control group (CON; n = 34) using a computer-generated randomization sequence. Group allocation was concealed using sequentially numbered, opaque, sealed envelopes (SNOSE), and the envelopes were opened by an independent research assistant after baseline testing to ensure allocation concealment and minimize selection bias.

During the 8-week intervention period, six participants (three from each group) withdrew for personal reasons (lack of interest, $n = 4$; health issues, $n = 2$), resulting in a final sample of 62 participants (INT: $n = 31$, CON: $n = 31$) for data analysis. Written informed consent was obtained from all participants prior to enrollment, and they were informed of their right to withdraw from the study at any time without penalty.

Eight-week long intervention protocol, with a frequency of four sessions of 80–90 minutes per week, was implemented in the study. Each training session followed a structured format consisting of a 15-minute warm-up, 50–60 minutes of key intervention exercises, and a 10-minute cool-down with stretching. Progressive overload was applied by increasing intensity and difficulty every two weeks. The intervention targeted four main domains:

- Plyometrics: Squat jumps, box jumps, and lateral hops to improve power and landing mechanics.
- Strength Training: Emphasis on bodyweight exercises such as Nordic hamstring curls and

single-leg squats.

- Dynamic Stability and Balance: Single-leg balances on unstable surfaces and Y-balance test reaches.
- Agility and Sport-Specific Exercises: Change-of-direction drills with focus on deceleration and cutting technique.

The week-wise structure of the INT sessions is presented in Table 1, detailing the progression of training components across the intervention period.

During the intervention period, the control group continued their regular training, which consisted of technical and tactical exercises, without participating in any structured neuromuscular training program. Before the intervention, demographic and anthropometric data were recorded for all participants. These included age, height, weight and body mass index (BMI).

Intervention Protocol

To ensure consistency in training volume and intensity, the control group's activities were regularly monitored throughout the intervention period. Their weekly schedule included five sessions lasting 90 minutes each. These sessions began with a standardized 15-minute warm-up consisting of low-intensity jogging and stretching. This was followed by 45 minutes of technical and tactical drills such as passing, dribbling, kicking and heading, and concluded with 30 minutes of simulated match play. The control group did not participate in any structured neuromuscular, plyometric or eccentric strength training activities included in the intervention protocol. To evaluate the effects of the intervention, a series of standardized physical performance tests was administered before and after the training period. These included:

Tuck Jump Assessment (TJA): The TJA is a dynamic plyometric test used to identify biomechanical deficits of the lower limbs, particularly poor landing mechanics, which are closely associated with the risk of ACL injury. A 10-second video recording was made for each participant while performing repeated tuck jumps. The recordings were analyzed using a standardized 10-point checklist focusing on knee valgus, thigh asymmetry, and landing control. Lower scores indicated better performance and reduced biomechanical risk.

Isokinetic Strength Testing: A Humac Norm isokinetic dynamometer was used to assess the peak torque of the hamstring and quadriceps muscles in the dominant leg. Measurements were taken at two angular velocities: 60°/s for conventional strength and 300°/s for functional strength. Based on these values, two strength ratios were calculated: the Conventional Hamstring-to-Quadriceps ratio (Hcon:Qcon) at 60°/s and the Functional Hamstring-to-Quadriceps ratio (Hexc:Qcon).

Active Knee Extension (AKE) Test: The AKE test was used to measure hamstring flexibility. Participants lay supine with the hip flexed to 90 degrees and were instructed to extend the knee until a maximal stretch was felt. The angle of knee extension was measured using a goniometer. Greater angles indicated better hamstring flexibility.

Quality Assurance and Fidelity Measures: All assessors involved in the study were qualified experts in sports sciences and physical education, with prior experience in isokinetic testing and biomechanical assessment. Tuck Jump Assessment (TJA) was evaluated by two blinded raters who independently scored the video recordings. The intra-class correlation coefficient (ICC) for their pre-intervention scores was excellent (ICC[2,1] = 0.91), indicating high inter-rater reliability. The Humac Norm isokinetic dynamometer was calibrated before each testing session according to the manufacturer's specifications. For the Active Knee Extension (AKE) test, a standard universal goniometer was used, with its axis precisely aligned with the lateral femoral epicondyle. To ensure fidelity to the training protocol, all INT sessions were supervised by a certified strength and conditioning specialist. Attendance logs were maintained to monitor adherence. An overall adherence rate of 94 percent was recorded, reflecting strong participant compliance with the intervention protocol.

Statistical Analysis

Data were analyzed using the Statistical Package for the Social Sciences (SPSS), version 27. The Shapiro–Wilk test was applied to assess the normality of data distribution. Independent *t*-tests were used to compare baseline values between groups. A mixed-model analysis of variance

Table 1. Week-wise INT Training Schedule

Week	Warm-up Activities	Key Intervention Components	Cool-down
1–2	Jogging, dynamic stretches (15 min)	Basic plyometrics, bodyweight squats, balance on stable surface	Static stretching (10 min)
3–4	Jogging + mobility drills	Intermediate plyometrics, Nordic curls intro, single-leg balance	Dynamic stretches
5–6	Jogging + ladder drills	Advanced plyometrics, eccentric hamstring strengthening, unstable surface balance	Hamstring-focused stretches
7–8	Cone drills + coordination	Deceleration + cutting drills, peak strength work, combined tasks	Sport-specific stretches

(ANOVA) was employed to examine group-by-time interactions across outcome measures. Effect sizes were calculated using Cohen's *d*, with thresholds of 0.2, 0.5, and 0.8 indicating small, medium, and large effects, respectively [31].

Results

Baseline demographic and anthropometric characteristics of the participants are presented in Table 2.

Following the data in Table 2, no statistically significant differences were observed between the intervention and control groups at baseline across any measured variable ($p > 0.05$). This indicates that randomization was successful, ensuring that any post-intervention differences could be attributed to the effects of the intervention itself.

Pre- and post-intervention results for all primary outcome measures in both groups are summarized in Table 3.

Following the results presented in Table 3, the intervention group showed statistically significant improvements in all assessed variables between pre- and post-test. In contrast, the control group exhibited no significant changes in any of the outcomes.

The results of the Shapiro–Wilk test used to evaluate the normality of distribution for all outcome variables are presented in Table 4.

As shown in Table 4, all *p*-values exceeded the conventional threshold of 0.05, indicating that the data for each variable were normally distributed at both time points in both groups. This confirmed the suitability of applying parametric statistical tests, such as mixed-model ANOVA and independent samples *t*-tests, in subsequent analyses.

Table 2. Baseline Demographic and Anthropometric Characteristics of Participants

Variable	Intervention Group (n=31)	Control Group (n=31)	p-value
Age (years)	17.1 ± 0.8	17.3 ± 0.7	0.45
Height (cm)	172.4 ± 5.6	173.1 ± 6.1	0.62
Weight (kg)	61.5 ± 7.2	62.8 ± 6.5	0.48
BMI (kg/m²)	20.7 ± 1.9	21.0 ± 1.7	0.55
Playing Experience (years)	4.5 ± 1.2	4.7 ± 1.1	0.52

Note: Data are presented as mean ± standard deviation. p-values are based on independent samples t-tests.

Table 3. Pre- and Post-Intervention Scores for Primary Outcome Measures (Mean ± SD)

Outcome Measure	Group	Pre-Test	Post-Test	p-value (Within-Group)
TJA Score	INT	6.5 ± 1.4	3.2 ± 1.1*	<0.001
	CON	6.3 ± 1.6	6.1 ± 1.5	0.58
Hamstring PT 60°/s (Nm)	INT	98.2 ± 14.5	121.6 ± 16.8*	<0.001
	CON	96.8 ± 15.1	97.5 ± 14.3	0.84
Hcon:Qcon Ratio (%)	INT	52.1 ± 5.8	61.4 ± 6.2*	<0.001
	CON	51.7 ± 6.1	52.0 ± 5.9	0.82
Hexc:Qcon Ratio (%)	INT	72.3 ± 7.1	85.9 ± 8.4*	<0.001
	CON	71.8 ± 6.5	72.5 ± 7.0	0.67
AKE Test (°)	INT	142.5 ± 9.8	157.8 ± 8.5*	<0.001
	CON	141.2 ± 10.5	142.1 ± 9.7	0.71

Note: INT = Intervention Group; CON = Control Group; TJA = Tuck Jump Assessment; PT = Peak Torque; AKE = Active Knee Extension; denotes a statistically significant difference between pre- and post-test scores within the same group ($p < 0.001$); p-values are from within-group comparisons using repeated measures.

Table 4. Results of Shapiro–Wilk Test for Normality of Data

Variable	Group	Statistic (W)	p-value
Age (years)	Intervention	0.978	0.721
	Control	0.981	0.802
Height (cm)	Intervention	0.966	0.358
	Control	0.971	0.485
Weight (kg)	Intervention	0.961	0.267
	Control	0.974	0.612
TJA Score (Pre)	Intervention	0.970	0.467
	Control	0.968	0.412
TJA Score (Post)	Intervention	0.976	0.674
	Control	0.972	0.538
Hamstring PT 60°/s (Pre)	Intervention	0.986	0.934
	Control	0.977	0.693
Hamstring PT 60°/s (Post)	Intervention	0.973	0.558
	Control	0.983	0.865
Hcon:Qcon Ratio (Pre)	Intervention	0.984	0.889
	Control	0.979	0.755
Hcon:Qcon Ratio (Post)	Intervention	0.975	0.635
	Control	0.981	0.815
AKE Test (Pre)	Intervention	0.969	0.439
	Control	0.976	0.661
AKE Test (Post)	Intervention	0.977	0.687
	Control	0.974	0.599

Note: The Shapiro–Wilk test was applied to assess the normality of pre- and post-intervention scores for each outcome measure in both the intervention and control groups. p-values greater than 0.05 indicate no significant deviation from normality.

Effect sizes (Cohen's *d*) were calculated to quantify the magnitude of between-group differences in outcome changes from pre- to post-intervention. These results are presented in Table 5.

As shown in Table 5, the intervention produced a very large effect on landing mechanics as measured by the Tuck Jump Assessment (d = 2.41). Additionally, large effects were observed for hamstring strength (PT at 60°/s), hamstring-to-quadriceps ratios (Hcon:Qcon and Hexc:Qcon), and hamstring flexibility (AKE test), indicating strong practical relevance of the intervention across all key performance outcomes.

Discussion

This study aimed to evaluate the effects of an eight-week integrated neuromuscular training (INT) program on modifiable risk factors associated with anterior cruciate ligament (ACL) and hamstring strain injuries (HSIs) in adolescent football players. The findings demonstrated that participants in the INT group showed significant improvements

Table 5. Between-Group Effect Sizes (Cohen's d) for Changes in Outcome Measures

Outcome Measure	**Cohen's *d***	**Magnitude**
TJA Score	2.41	Very Large
Hamstring PT 60°/s	1.55	Large
Hcon:Qcon Ratio	1.56	Large
Hexc:Qcon Ratio	1.73	Large
AKE Test	1.89	Large

Note: Effect sizes were calculated using Cohen's d to compare the magnitude of changes between the intervention and control groups. The following thresholds were used for interpretation: 0.2 = small, 0.5 = medium, 0.8 = large.

across all primary outcome measures, including landing biomechanics, eccentric hamstring strength, muscle strength ratios (Hcon:Qcon and Hexc:Qcon), and hamstring flexibility. In contrast, no statistically significant changes were observed in the control group. The magnitude of between-group differences, confirmed by large to very large effect sizes, further underscores the practical significance of the intervention.

Anterior cruciate ligament (ACL) and hamstring strain injuries (HSIs) are among the most prevalent and functionally limiting injuries in football [32]. The findings of the present study support the original hypothesis, demonstrating that participants in the INT group experienced significant improvements across all assessed variables compared to those in the control group, who continued with routine training.

The most notable result was a 51% reduction in the Tuck Jump Assessment (TJA) score within the intervention group, accompanied by a very large effect size ($d = 2.41$; see Table 4). This improvement highlights the effectiveness of the INT protocol in addressing neuromuscular risk factors associated with ACL injury. Kember [33] previously identified the TJA as a valid and practical tool for assessing high-risk movement patterns, particularly those linked to non-contact ACL injuries, such as hip internal rotation, dynamic knee valgus, and inadequate limb control.

The scale of improvement observed in this study exceeds that reported in earlier interventions with shorter session durations or lower training frequencies. This suggests that both the dosage and duration of the INT protocol played a critical role in producing measurable neuromuscular adaptations. Specifically, the eight-week program, which included four sessions per week lasting 80–90 minutes and followed a progressive overload structure, appears to have been sufficient to elicit meaningful improvements in landing mechanics among adolescent players.

Kember et al. [34] reported that reductions in Tuck Jump Assessment (TJA) scores are indicative of improved neuromuscular control. Consistent with this, the present study observed a 51% decrease in TJA scores among participants in the intervention group, reflecting substantial neuromuscular adaptations. These improvements were evident in enhanced biomechanical performance during landing tasks.

Similarly, Dhahbi et al. [35] concluded that proper knee alignment and stable trunk positioning during jumping contribute to improved balance, lower limb control, and overall athletic performance. In line with this, the present intervention emphasized safe landing techniques and correct knee positioning, which likely contributed to improved body control and stability upon landing.

These findings are further supported by Franco et al. [36], who demonstrated that integrated neuromuscular training positively influences the structural and functional stability of the knee joint, thereby enhancing protection of the ACL and surrounding soft tissues. Moreover, the current results align with the conclusions of Souaifi et al. [37], who emphasized that neuromuscular training provides a solid foundation for reducing ACL injury risk in youth sports.

Leahy et al. [38] emphasized that addressing dual injury risks, such as anterior cruciate ligament and hamstring injuries in adolescent football players, remains a key area of research. The development of training protocols that simultaneously enhance performance and reduce injury risk in youth football has been recognized as a promising and innovative approach [39]. Ribeiro et al. [40] noted that a lack of comprehensive studies examining interventions capable of concurrently improving performance indicators and mitigating injury risks among adolescent players represents a significant gap in the current literature.

Corroborating the findings of Liveris et al. [5], the present results confirm the efficacy of the integrated neuromuscular training (INT) program in producing measurable improvements in risk factors related to hamstring injuries. A 24 percent increase in hamstring strength, along with improvements in both conventional and functional hamstring-to-quadriceps ratios, supports the role of INT in restoring muscular balance. From a biomechanical perspective, the functional ratio represented by Hexc:Qcon is particularly relevant. It reflects the capacity of the hamstring muscles to control rapid leg extension during high-speed running, which is a key factor in the prevention of hamstring strains [41]. The observed large effect sizes (d = 1.56 to 1.73) further validate the practical effectiveness of the intervention, as shown in Table 5. These improvements are likely attributable to the inclusion of the Nordic Hamstring Exercise (NHE) in the training protocol. Importantly, the incorporation of NHE within a broader neuromuscular framework contributes to the novelty of this study.

Afonso et al. [42] reported that hamstring stability, flexibility, and strength are essential for safe athletic performance and injury prevention. The combined effects of all components of the integrated neuromuscular training (INT) program, including the Nordic Hamstring Exercise (NHE), contributed to enhanced hamstring function. In addition, the incorporation of sport-specific deceleration drills alongside single-leg stability exercises likely facilitated improved movement control and muscular output.

The Active Knee Extension (AKE) test results demonstrated a significant improvement in hamstring flexibility, as shown in Table 2. This flexibility gain may serve as an additional protective factor during high-intensity sports activities [43]. Recognizing the dual importance of strength and flexibility, Muanjai et al. [44] emphasized their critical role in supporting safe muscle performance and long-term muscle-tendon health. Increased flexibility is particularly relevant for adolescents, who are undergoing physiological transitions that heighten susceptibility to muscular stress and strain [45]. The inclusion of both dynamic and static stretching exercises in the intervention protocol likely contributed to improvements in flexibility and the functional performance of the muscle-tendon unit.

The present study applied and evaluated the INT protocol for addressing both anterior cruciate ligament and hamstring injury risks in a previously unexamined, low-resource adolescent male cohort. The findings demonstrate that the protocol can be implemented in settings where the use of multiple specialized interventions is limited. Unlike many studies that focus on either ACL or hamstring injury prevention, this research examined both outcomes within a single intervention.

Bathe et al. [46] reported that integrated neuromuscular training can improve muscular performance, which supports the current findings. Similarly, Ferrández-Laliena et al. [47] found that structured training contributes to improved landing mechanics and hamstring strength, which are essential for reducing injury risk. This type of combined approach may be suitable for addressing the multifactorial nature of neuromuscular control and injury prevention [48]. In line with the findings of Babayev et al. [49], the present results suggest that INT can be aligned with the physiological demands of sport in adolescent populations. By implementing a combined training protocol, the study provides information relevant to coaches and practitioners regarding feasibility and applicability under practical constraints.

Limitations of the Study

Several limitations should be considered when interpreting the findings. The sample included only 62 male adolescent football players from a single geographic location (Lakki Marwat), which may limit the generalizability of the results to broader or more diverse populations. Due to gender-related differences such as hormonal profiles, neuromuscular characteristics, and anatomical structure, the results are not applicable to female athletes. Furthermore, performance-related indicators such as sprinting, jumping, and dribbling were not assessed during this study. Including such metrics could have provided additional insights into the functional impact of the intervention.

Future Research Directions

Given the documented differences in injury risk profiles between male and female athletes, future studies should examine the effects of integrated neuromuscular training in adolescent female football players. Sex-specific interventions may support the development of targeted preventive strategies. Future investigations should also aim for larger, more diverse samples and consider long-term follow-up to assess sustained effects of the intervention. In addition, incorporating performance-based outcome measures into future protocols may enhance the practical applicability of the intervention in sports settings.

Conclusions

The findings of this study indicate that the 8-week integrated neuromuscular training (INT) program was effective in concurrently reducing modifiable risk factors associated with anterior cruciate ligament (ACL) injuries and hamstring strain injuries (HSIs) in adolescent male football players. Improvements in landing biomechanics, reflected by a substantial reduction in Tuck Jump Assessment scores, suggest a lower risk of movement patterns linked to ACL injuries. Additionally, increases in hamstring strength were accompanied by enhancements in flexibility and both conventional and functional hamstring-to-quadriceps ratios, which are associated with reduced HSI risk. Large effect sizes observed across all measured variables support the relevance of the intervention. This study contributes to existing literature by evaluating a single, structured protocol that addresses multiple injury risk factors in a population with limited access to specialized training resources.

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Conflict of Interest

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

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ORIGINAL ARTICLE

Effects of an eight-week neuromuscular training program on performance variables in female university football players

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

Abstract

Background and Study Aim Football performance depends on the integration of speed, strength, agility, and balance, all of which contribute to efficient movement and injury prevention. Neuromuscular training (NMT) is widely used to improve these attributes by combining strength, plyometric, balance, and coordination exercises within a structured program. Although various training methods are applied in football conditioning, their relative effectiveness in enhancing multiple performance domains simultaneously remains a matter of practical interest. The aim of this study was to examine the effects of an eight-week NMT program on sprint performance, explosive power, change-of-direction (COD) ability, and dynamic balance in female university football players.

Material and Methods A total of 41 athletes were initially screened. Thirty-four athletes aged 20–24 years met the inclusion criteria and were randomly assigned to either an experimental group (EXP, n = 17) or a control group (CON, n = 17). The EXP group completed structured NMT sessions three times per week alongside regular football training. The CON group continued standard practice without additional training. Pre- and post-intervention tests included the 50-m sprint, standing broad jump, 505 COD test, and Y-Balance Test. Statistical analyses included paired t-tests, ANCOVA, and repeated measures ANOVA. Effect sizes were calculated using Cohen's dz and partial eta squared.

Results The EXP group showed significant within-group improvements across all outcomes ($p < .001$, Cohen's dz = 1.07–1.24). The CON group demonstrated no meaningful changes. Between-group comparisons showed significant differences for all performance variables (all $p < .01$), with large effect sizes ($\eta^2 p$ = 0.28–0.35). Correlation analysis revealed strong associations between improvements in dynamic balance, COD, and sprint performance ($r = -0.56$ to $+0.62$, $p < .01$). Sensitivity analyses confirmed that the findings remained robust after excluding low adherence and outlier cases.

Conclusions An eight-week NMT program led to significant improvements in speed, power, agility, and balance among female university football players. The results highlight the effectiveness of integrated neuromuscular interventions in enhancing multidimensional performance characteristics in this population

Keywords: physical education, sports performance, agility training, dynamic balance, plyometric exercise, women's football.

Introduction

Football continues to evolve as a physically demanding and tactically complex sport, requiring players to cope with frequent, high-speed movements in multiple directions. Sprinting, cutting, jumping, and sudden changes in pace occur repeatedly throughout a match, alternating with brief periods of lower activity [1, 2]. To perform effectively, athletes must develop physical qualities that support efficient movement and reduce fatigue during play. Speed, power, agility, directional control, and balance all contribute directly to performance outcomes and help reduce the likelihood of injury [3, 4].

Neuromuscular training (NMT) offers a structured way to improve multiple physical capacities by combining strength exercises with plyometrics, balance work, agility drills, and sprint tasks. Unlike isolated methods that focus on a single skill, NMT develops coordination between different movement systems to improve performance and reduce injury risk [5, 6]. It targets neural processes such as motor-unit recruitment, reflex control, and movement coordination, which are especially important for explosive and reactive actions in football [7, 8]. Even short training periods can lead to measurable gains

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in power, sprinting form, directional speed, and balance control [9–11]. In recent years, NMT has received more attention in women's football due to its practical value in improving movement and lowering injury risk. For example, Roso-Moliner et al. (2023) reported that a 10-week program improved sprinting, agility, and jumping performance, while also reducing side-to-side differences in lower limbs among female players [12].

Female athletes represent a group in which neuromuscular factors have specific practical importance. Studies show that women may be more prone to certain movement-related injuries, including anterior cruciate ligament (ACL) rupture. This is partly linked to differences in landing technique, joint stability, and neuromuscular control [13, 14]. Programs that improve postural control, balance, and muscle response to sudden forces are therefore especially relevant for this population. Although more women are now involved in football, most training research still focuses on male athletes [15, 16]. Shifting attention to female players helps strengthen both applied practice and the evidence base in sports science.

One of the main advantages of neuromuscular training (NMT) is that it targets several aspects of athletic performance at the same time. In contrast, traditional training often focuses on a single capacity. For example, resistance training is used to build strength, and sprint drills are applied to improve speed. However, these approaches may overlook the coordination required for effective multidirectional movements. Research indicates that NMT can lead to broader improvements by combining explosive exercises with tasks that challenge balance and movement control [17]. Plyometric exercises support the stretch-shortening cycle and improve reactive strength. Sprint drills develop both horizontal and vertical force production. COD training builds braking ability and re-acceleration. Balance tasks improve sensorimotor control. These components work together to build a movement base that supports performance and may help reduce injury risk [18, 19].

Sprint performance is an important element in football. Players often cover short bursts of high-speed running to gain position or reach the ball ahead of an opponent [20, 21]. Improving this ability depends not only on muscle power but also on neuromechanical control. Specifically, athletes must direct force horizontally and reduce braking during ground contact. Neuromuscular training (NMT) targets these qualities through resisted sprints, bounding exercises, and sprint technique drills. These methods have been associated with improvements in acceleration and maximum speed [22, 23].

Explosive power is also essential. It is often assessed through jumping tests and contributes to both sprinting and aerial actions. Studies report that the plyometric elements of NMT improve vertical and horizontal jump performance. This is achieved by increasing stretch-shortening cycle (SSC) efficiency and tendon stiffness [24, 25].

Change-of-direction (COD) ability depends on eccentric braking strength, control of the trunk and pelvis, and quick transitions from stopping to starting again [26, 27]. COD drills used in neuromuscular training (NMT) help athletes develop these skills. Dynamic balance, although sometimes overlooked, also contributes to movement efficiency and injury prevention. Training that includes core and balance exercises has been shown to improve postural stability [28, 29, 30].

Research shows that neuromuscular programs combining different types of exercises can lead to gains in sprinting, agility, balance, and jump performance. These effects have been observed in athletes across a wide age range [31, 32, 33]. However, female university players are still studied less often than youth or elite professionals [15, 16].

Analysis of research findings has shown that neuromuscular training (NMT) improves several components of athletic performance, including sprinting, agility, jumping, and balance. Researchers emphasize that these adaptations are particularly important in sports requiring rapid, multidirectional actions such as football. Authors also highlight the role of structured and integrative programs that combine strength, coordination, and control-oriented exercises. Although NMT has been widely studied among youth and mixed athlete groups, comparatively fewer investigations have focused on female university players. Existing studies confirm that neuromuscular interventions enhance speed, agility, balance, and jump performance across age categories [31, 32, 33]. However, questions remain about how female athletes respond to different training loads, progressions, and program designs within football contexts. This ongoing uncertainty limits the practical use of targeted interventions in university-level settings, where female athletes train intensively but often lack the professional support available to elite players. To explore this issue, the present study examined the effects of an eight-week NMT program on sprint performance, explosive power, change-of-direction ability, and dynamic balance in female university football players.

Materials and Methods

Participants of the Study

Forty-one female athletes initially volunteered to participate in the study. Seven were excluded due to medical conditions that made participation unsafe. The final sample consisted of thirty-four university-level female football players aged 20 to 24 years (mean ± SD = 21.8 ± 1.3 years). All participants had at least three years of structured training experience and were actively involved in competitive university football. Demographic and baseline characteristics of the participants are summarized in Table 1.

Table 1. Demographic characteristics of participants (n = 34)

Variable	Experimental Group (n = 17)	Control Group (n = 17)	p-value
Age (years)	21.7 ± 1.4	21.9 ± 1.2	.68
Height (cm)	162.8 ± 5.7	163.5 ± 6.1	.74
Body mass (kg)	58.2 ± 6.4	57.6 ± 6.1	.82
Playing experience (years)	5.4 ± 1.2	5.3 ± 1.1	.79

Note. Values are presented as mean ± standard deviation. Independent samples t-tests showed no significant differences between groups (all p > .05), indicating that baseline characteristics were comparable.

Athletes were recruited from local university sports programs and agreed to take part voluntarily after receiving detailed information about the study procedures. Inclusion criteria required participants to be in good health, free of injury during the previous six months, and not involved in any additional structured resistance or plyometric training. Exclusion criteria included recent musculoskeletal injury, neurological disorders, or absence from more than 10 percent of scheduled sessions.

Participants were randomly assigned to either an experimental group (EXP, n = 17), which completed the neuromuscular training program, or a control group (CON, n = 17), which continued regular football training without any additional intervention. Randomization was performed using a computerized random number generator.

All participants provided written informed consent prior to the start of the study. Ethical approval was obtained from the Institutional Human Ethics Committee and the procedures followed the principles outlined in the Declaration of Helsinki.

The recruitment, allocation, and follow-up process for all participants is outlined in the CONSORT flow diagram. This includes the number of athletes assessed for eligibility, reasons for exclusion, and group assignment, as well as adherence and retention throughout the study. An overview of the participant flow is shown in Figure 1.

Procedures

Intervention Design

This study used a randomized controlled trial (RCT) design with pre- and post-test assessments conducted over an 8-week period. Thirty-four female football players were randomly assigned to either an experimental group (EXP, n = 17), which completed an additional neuromuscular training (NMT) program, or a control group (CON, n = 17), which continued with regular football training.

Performance tests were conducted at baseline and after the intervention. These included the 50-meter sprint, standing broad jump, 505 change-of-direction (COD) test, and the Y-Balance Test. All testing was carried out under standardized conditions.

EXP group training sessions were held three times per week (75 minutes per session on Monday, Wednesday, and Friday). Each session followed a structured format that included a warm-up, a progressive neuromuscular training block, and a cool-down. The program was delivered either on the university football field or in an indoor hall, depending on weather conditions. All sessions were supervised by certified strength and conditioning specialists, maintaining a coach-to-athlete ratio of 1:8.

Training intensity progressed over time. In weeks 1 to 2, intensity was set at 40 to 50 percent of maximum effort and increased to 70 to 80 percent by weeks 7 to 8. Sets, repetitions, and rest intervals were controlled and adjusted according to progression (Table 2).

The intervention included football-specific drills, such as sprint technique work, plyometric exercises, COD tasks, and balance activities. These components are directly related to functional demands in football. Importantly, the NMT program was integrated into the athletes' existing football training routines. This approach ensured ecological validity by reflecting real-world competitive training conditions.

The CON group continued with regular football training and did not receive any additional neuromuscular input. Both groups were instructed to maintain their usual dietary habits and daily routines throughout the study period.

Training fidelity and intensity monitoring:

To ensure reproducibility, session fidelity was monitored through attendance logs and coach supervision checklists. Exercise intensity was prescribed using the Borg CR-10 Rate of To support reproducibility, training fidelity was monitored using attendance logs and weekly coach supervision checklists. Exercise intensity was regulated with the Borg CR-10 Rate of Perceived Exertion (RPE) scale, progressing from RPE 4 to 8 (light to very hard). For resisted sprints, the load was set at approximately 10 percent of each athlete's body mass. Plyometric drills were performed with ground contact times kept below 0.25 seconds. Coaches monitored adherence weekly, and average session compliance exceeded 90 percent.

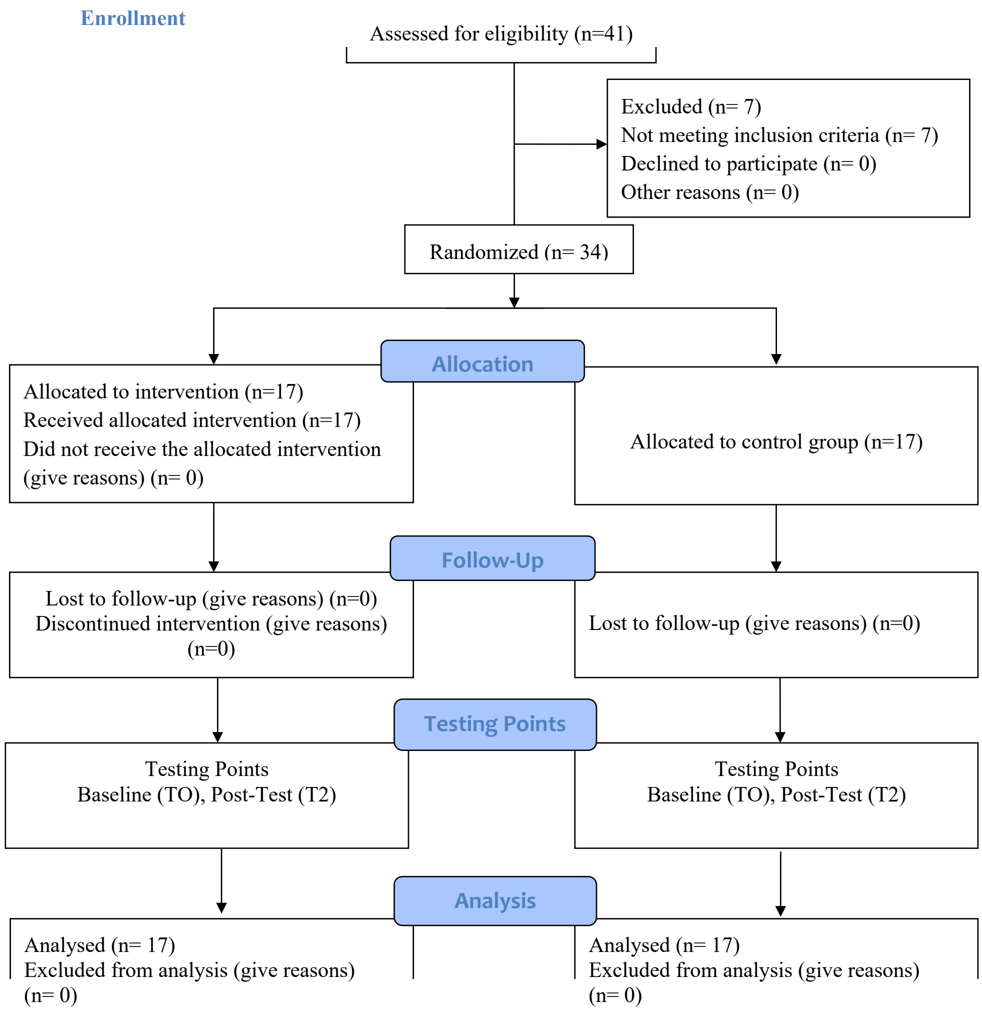

Figure 1. CONSORT flow diagram of participants

The control group maintained their standard football schedule, which included 3 to 4 weekly team sessions lasting 90 to 100 minutes. These sessions consisted of tactical drills, small-sided games, and aerobic conditioning. However, no structured plyometric or neuromuscular elements were included. Training loads for both groups were tracked using the session-RPE method (RPE × duration) to confirm comparability of total workload exposure.

The training protocol shown in Table 2 followed a three-phase format: warm-up, main neuromuscular block, and cool-down. Intensity and complexity increased progressively across the eight weeks. Exercise intensity was prescribed using the Borg CR-10 RPE scale, beginning with RPE 4–5 in weeks 1–2 and reaching RPE 7–8 in weeks 7–8. Load progression was tailored using supervised feedback and individual monitoring. Athlete adherence exceeded 90 percent, verified through attendance records, coach oversight, and weekly video reviews. Rest intervals were standardized and enforced by coaching staff. The control group maintained regular football training of similar volume and duration but without any additional neuromuscular elements.

Four outcome variables were assessed in this study:

1. *Sprint Speed*. Measured using the 50-meter dash test. Time was recorded to the nearest 0.01 seconds using electronic timing gates (Brower Timing Systems, Draper, UT, USA) [34].
2. *Explosive Power*. Assessed with the Standing Broad Jump (SBJ) test. Distance (in meters) was measured from the take-off line to the nearest point of heel contact using a calibrated measuring tape [35].
3. *Change-of-Direction (COD) Speed*. Evaluated using the 505 COD test. Timing gates were placed at 5 and 10 meters. Athletes completed two trials per leg, and the best time was used for analysis [36].
4. *Dynamic Balance*. Measured using the Y-Balance Test – Lower Quarter (YBT-LQ). Reach distances (in centimeters) were recorded in the anterior, posteromedial, and posterolateral directions. Scores were normalized to leg length, and a composite score was calculated [37].

All tests used in the study have demonstrated acceptable reliability in previous research

Table 2. Eight-Week Neuromuscular Training Protocol for the Experimental Group

Week	Frequency & Session Length	Structure	Key Exercises	Sets × Reps	Intensity Prescription	Rest
1–2	3 sessions/week (Mon, Wed, Fri); 75 min	Warm-up (15 min): light jogging, mobility, dynamic stretching. Main block (50 min): introductory plyometrics, sprint mechanics, balance and core control drills. Cool-down (10 min): static stretching, breathing.	Squat jumps, lateral bounds, front planks, Y-balance reach	2 × 8	RPE 4–5 (≈ 50% max effort)	45 s
3–4	3 sessions/ week; 75 min	Progressive overload phase I with horizontal propulsion and short sprints.	Box jumps, resisted sprints (10–20 m, 10% body mass), single-leg hops, shuttle runs	3 × 10	RPE 5–6 (≈ 60% max), moderate velocity	60 s
5–6	3 sessions/ week; 75 min	Progressive overload phase II with increased volume and eccentric focus.	Depth jumps (0.45 m), 30 m sprints, 505 COD drills, unstable-surface balance tasks	4 × 12	RPE 6–7 (≈ 70% max), contact time < 0.25 s	75 s
7–8	3 sessions/ week; 75 min	Performance integration with reactive stimuli and ball drills.	Bounding, repeated sprints (10–40 m), advanced COD with ball, single-leg box jumps (0.3 m)	5 × 14	RPE 7–8 (≈ 80% max), near-max velocity	90 s

Note. RPE = Borg CR-10 Rate of Perceived Exertion; COD = change-of-direction; s = seconds; m = meters.

(intraclass correlation coefficient, ICC = 0.80–0.95). A familiarization session was conducted one week prior to baseline testing to minimize learning effects.

Statistical Analysis

All analyses were performed using IBM SPSS Statistics (Version 26). Data normality was assessed with the Shapiro–Wilk test. Descriptive statistics are reported as mean ± standard deviation for all variables. Within-group (pre-to-post) changes were evaluated using paired-samples t-tests. Between-group differences were analysed using analysis of covariance (ANCOVA), with baseline values included as covariates. Effect sizes were calculated as Cohen's d for within-group comparisons and Hedges' g (with correction for small sample size) for between-group comparisons. Ninety-five percent confidence intervals (95% CIs) were reported for all mean changes and group differences. Two sensitivity analyses were performed: (a) excluding participants with adherence below 90 percent, and (b) removing extreme outliers defined as values more than three standard deviations from the group mean. In both cases, the results remained consistent with the main findings. Statistical significance was set at $p < .05$.

Results

All 34 participants completed the 8-week intervention, and full datasets were available for analysis. No adverse events were reported during the study. At baseline, the experimental and control groups were statistically comparable in terms of age, body mass, height, and training experience (all $p > .05$; Table 1). Attendance in the experimental group was high, with participants completing over 90 percent of the scheduled training sessions. Normality testing confirmed that all variables were normally distributed, allowing the use of parametric statistical procedures. The intervention led to marked improvements across all performance outcomes in the experimental group. In contrast, only minimal changes were observed in the control group.

Results of the Shapiro–Wilk test (all $p > .05$) indicated no significant departures from normality, confirming that parametric analyses were appropriate for all variables presented in Table 3.

The effects of the 8-week intervention within each group are summarized in Table 4, which presents pre- and post-test means, t-values, p-values, effect sizes, and confidence intervals for all performance variables.

The results presented in Table 4 show that the experimental group achieved statistically significant improvements across all performance outcomes following the 8-week neuromuscular training program ($p < .001$ for all tests). The largest gains were observed in sprint time and standing broad jump distance, both showing large effect sizes ($dz > 1.15$), indicating substantial enhancement in linear speed and explosive power. Similarly, change-of-

Table 3. Shapiro-Wilk normality test results for study variables (n = 34)

Variable	Group	Pre-test (p-value)	Post-test (p-value)
50-m Sprint (s)	Experimental	0.231	0.188
	Control	0.274	0.301
Standing Broad Jump (m)	Experimental	0.162	0.205
	Control	0.243	0.198
505 COD Test (s)	Experimental	0.211	0.174
	Control	0.229	0.256
Y-Balance Composite (%)	Experimental	0.184	0.193
	Control	0.209	0.247

Table 4. Within-group Pre–Post Changes (Paired t-tests, Cohen's dz, 95% CI)

Variable	Group	Pre-test (M ± SD)	Post-test (M ± SD)	t(16)	p-value	Cohen's dz	95% CI for Δ
50-m Sprint (s)	Experimental	7.42 ± 0.41	7.02 ± 0.38	5.12	<.001	1.24	[−0.54, −0.28]
	Control	7.45 ± 0.39	7.41 ± 0.42	1.02	.319	0.24	[−0.11, 0.04]
Standing Broad Jump (m)	Experimental	1.92 ± 0.18	2.07 ± 0.16	4.88	<.001	1.18	[0.09, 0.21]
	Control	1.93 ± 0.17	1.94 ± 0.18	0.58	.571	0.14	[−0.02, 0.05]
505 COD Test (s)	Experimental	2.48 ± 0.12	2.34 ± 0.11	4.39	<.001	1.07	[−0.20, −0.07]
	Control	2.47 ± 0.13	2.46 ± 0.12	0.41	.687	0.10	[−0.04, 0.03]
Y-Balance Composite (%)	Experimental	93.4 ± 3.2	97.8 ± 2.9	4.62	<.001	1.12	[2.1, 6.7]
	Control	93.6 ± 3.3	93.9 ± 3.5	0.77	.450	0.19	[−0.5, 1.1]

Note. Within-group effect sizes in the experimental group ranged from dz = 1.07 to 1.24, indicating large and practically meaningful improvements across all tested variables.

Table 5. ANCOVA Results with Partial Eta Squared

Variable	F-value	p-value	Partial η^2
50-m Sprint	14.62	0.001	0.35
Standing Broad Jump	12.35	0.002	0.32
505 COD Test	10.87	0.003	0.29
Y-Balance Composite	11.24	0.002	0.30

Note. ANCOVA revealed significant between-group differences for all performance outcomes (F = 10.87–14.62, p < .01), with large effect sizes (partial η^2 = 0.29–0.35), indicating that the experimental group demonstrated greater improvements than the control group after adjusting for baseline values.

direction speed and dynamic balance also improved significantly, reflecting enhanced neuromuscular control. In contrast, the control group did not exhibit statistically significant changes in any of the measured variables (p > .05), suggesting that regular football training alone was insufficient to elicit comparable adaptations over the same period.

The results of the ANCOVA analysis, which compared post-intervention outcomes between groups while adjusting for baseline values, are summarized in Table 5. As shown in Table 5, the experimental group achieved significantly better post-intervention results across all measured domains compared to the control group. These differences remained significant after adjusting for pre-test scores, confirming the specific effect of the neuromuscular training program. The largest between-group differences were observed in sprint performance and standing broad jump, with partial eta squared values exceeding 0.30, indicating large effects. Overall, the data support the conclusion that structured neuromuscular training provided superior benefits compared to routine football practice alone.

The results of the repeated measures ANOVA, testing for Group × Time interaction effects across performance outcomes, are summarized in Table 6. As shown in Table 6, repeated measures ANOVA revealed significant Group × Time interactions for all performance variables. These findings indicate that the pattern of change over the 8-week period differed substantially between the experimental and control groups. The most pronounced interaction effects were found for sprint speed and standing broad jump, where performance gains in the experimental group were not matched by the control group. Partial eta squared values ranging from 0.28 to 0.34 reflect large effect sizes, reinforcing the conclusion that the neuromuscular training program was responsible for the observed improvements.

Relationships between relative improvements in performance outcomes were examined using Pearson correlation coefficients. The results are presented in Table 7. As shown in Table 7, moderate to large correlations were found between improvements in balance, sprint speed, COD ability, and explosive power. Notably, participants who improved most in dynamic balance also tended to demonstrate faster sprint and COD times. Similarly, gains in jump performance were associated with sprint acceleration. These relationships suggest that different neuromuscular components may develop in parallel when exposed to integrative training stimuli, supporting the interconnected nature of adaptation within complex athletic tasks.

Sensitivity analyses confirmed the robustness of the findings. Excluding participants with adherence below 90 percent or removing statistical outliers (greater than 3 standard deviations from the group mean) did not alter the overall outcomes. All ANCOVA and repeated measures ANOVA results remained statistically significant ($p < .01$), with large within-group effect sizes (*Cohen's dz* = 1.07–1.24) maintained across all performance variables.

Discussions

This randomized controlled trial investigated whether an eight-week neuromuscular training (NMT) program could improve key physical performance qualities in female university football players. The intervention combined plyometric exercises, sprint mechanics, change-of-direction (COD) drills, and balance components. The findings show that athletes in the experimental group achieved consistent and statistically significant improvements across all measured domains. These gains were observed in comparison to peers who continued standard football practice. The differences were confirmed through both within-group analyses and baseline-adjusted between-group comparisons. The results support previous evidence that integrated neuromuscular protocols promote rapid improvements across multiple physical capacities in trained populations [11, 17, 38].

Neuromuscular training (NMT) is best understood as a combined stimulus rather than a single training modality. It integrates motor

Table 6. Repeated Measures ANOVA (Group × Time Interaction)

Variable	F (Group × Time)	p-value	Partial η²
50-m Sprint	13.48	0.001	0.34
Standing Broad Jump	11.92	0.002	0.31
505 COD Test	9.88	0.004	0.28
Y-Balance Composite	10.15	0.003	0.29

Note. Significant Group × Time interaction effects ($p < .01$) were observed across all performance variables, indicating that changes over time differed significantly between groups. Large interaction effect sizes (partial η^2 = 0.28–0.34) support the differential impact of the intervention.

Table 7. Correlation Analysis Between Improvements (%)

Variable Pair	r-value	p-value	Interpretation
% Y-Balance vs. Δ% 505 COD Test	-0.56	0.002	Large, inverse
% Y-Balance vs. Δ% 50-m Sprint	-0.48	0.006	Moderate, inverse
% 505 COD Test vs. Δ% 50-m Sprint	+0.62	<0.001	Large, positive
% Standing Broad Jump vs. Δ% 50-m Sprint	-0.44	0.011	Moderate, inverse

Note. Negative correlations indicate that greater improvements in balance and jump performance corresponded to faster (i.e. lower) sprint and COD times. Effect sizes ranged from moderate to large ($|r|$ = 0.44–0.62, all $p \leqslant .011$), suggesting meaningful interdependence between neuromuscular adaptations within the NMT program.

control, stretch-shortening cycle (SSC) function, strength and power expression, and movement skills within the same training mesocycle. Systematic reviews and meta-analyses have shown that, when properly progressed and supervised, this integrative approach produces improvements in speed, jump performance, change-of-direction (COD) ability, dynamic balance, and landing mechanics across athletic populations, including female athletes in field sports [5, 15, 31, 39, 40]. During interventions lasting six to ten weeks, early adaptations are typically driven by neural mechanisms. These include enhanced motor-unit recruitment, faster rate coding, improved inter- and intramuscular coordination, and increased pre-activation [8, 24, 38, 40, 41]. With longer exposure, structural adaptations become more pronounced. The present findings were obtained after eight weeks of training with coach supervision and progressive overload. They are consistent with this adaptation timeline and suggest that a single well-designed program can influence several physical capacities simultaneously [6, 11, 17, 39]. These outcomes also support previous studies in women's football. For instance, Roso-Moliner et al. reported improvements in sprinting and change-of-direction ability, along with reduced asymmetries, following a ten-week neuromuscular training program. These findings are comparable to the gains observed in the current study [12].

Linear sprint performance depends on both neuromuscular and technical factors. These include a stiffer leg spring during ground contact, precise orientation of horizontal and vertical force, coordinated extension at the hip, knee, and ankle joints, and reduced braking impulse during stance [3, 21, 42]. Interventions that combine plyometric training with resisted sprints or acceleration drills often lead to improvements in short-distance sprint ability among athletes in field sports [15, 22, 24, 43, 44]. The changes observed in the present study are consistent with those findings. These improvements can be explained by mechanisms such as enhanced musculotendinous stiffness, improved limb coordination, and shorter ground-contact time. Such adaptations can occur without significant changes in body mass over an eight-week period [7, 8, 25, 40, 41]. Importantly, studies involving female athletes have shown similar relative improvements when training intensity and supervision are scaled appropriately. This suggests that female sex alone is not a limiting factor for neuromuscular adaptation in sprint performance [6, 15, 16, 39].

Standing broad jump performance reflects the efficiency of the stretch-shortening cycle (SSC), the quality of eccentric–concentric coupling, and the coordination of movement from proximal to distal segments. Meta-analyses have shown that plyometric training improves jump outcomes when exercise progression is applied, landing mechanics are coached, and training volume is adapted to the athlete's experience [24, 43, 44]. In football and similar field sports, exercises such as unilateral hops, bounds, and depth-jump variations are closely related to horizontal propulsion and early-phase acceleration tasks [15, 16, 22, 45]. The improvements observed in this study align with those findings. The current results likely reflect the use of progressively loaded SSC-based exercises that involved both unilateral and bilateral actions. These outcomes are also supported by reports linking improved neuromuscular efficiency to better elastic energy utilization during the amortization phase [7, 8, 40, 41]. Additionally, studies on musculotendinous properties suggest that repeated SSC exposure increases tendon and aponeurotic stiffness in vivo. This adaptation enhances force transmission speed and contributes to the observed jump gains over mesocycle training periods [25].

Change-of-direction (COD) ability depends on more than just linear power. It is influenced by braking strength, the direction of force applied through the plant leg, trunk and pelvic stability, and the timing of re-acceleration [1, 2, 4]. COD is distinct from agility, which involves perceptual and decision-making demands. However, both are affected by neuromuscular qualities such as eccentric strength, coordination, and rate of force development [2, 26, 31, 41]. Previous studies show that plyometric and combined-method training programs can improve COD performance. These programs often include unilateral or lateral movements, as well as exercises targeting deceleration control. When delivered for six to ten weeks with proper progression and feedback, such interventions typically produce small to moderate improvements [22, 31, 33]. In the present study, the reduction in COD times following NMT is consistent with these results. Targeted drills may have improved braking mechanics, reduced knee valgus, and supported better trunk alignment. These changes allow for an earlier and more forceful push-off during the plant phase [1, 4, 26]. The inclusion of 505 drills and shuttle-run variations in the later weeks of training likely supported these adaptations through task-specific practice [4, 22, 33].

Dynamic balance improved together with speed and power in this study. Y-Balance Test and similar reach-based assessments are sensitive to changes following interventions that include balance training, proprioceptive stimulation, core stabilization, and lower-limb control. These tests demonstrate acceptable reliability when standardized procedures are followed [29, 30]. Programs that combine neuromuscular and balance-specific elements have been linked to improvements in postural control and movement coordination across both athletic and general populations [6, 11, 28]. In football players at the youth and university levels, similar neuromuscular interventions have led to parallel gains in balance and jump performance within comparable time frames [10, 11]. The structure of the present program included repeated exposure to single-leg hops, unstable-surface drills, and trunk stabilization tasks. These activities likely contributed to improvements in sensorimotor processing, anticipatory postural responses, and regulation of dynamic stiffness in lower-limb joints [13, 28, 30].

Performance variables such as sprinting, jumping, balance, and change-of-direction (COD) often improve together. These qualities share underlying neuromechanical factors, including motor-unit behavior, musculotendinous stiffness, coordination between body segments, and trunk and pelvic control [7, 8, 38, 41]. Research shows that unilateral balance and trunk stability can predict cutting performance beyond simple strength indicators. Similarly, improvements in COD and short sprint performance often occur together when training targets braking technique and horizontal force application [1, 4, 21, 42]. In this study, stronger gains in balance were associated with better COD and sprint outcomes. This pattern supports the idea that postural control contributes to efficient deceleration and re-acceleration during directional changes [1, 4, 26, 29]. Female athletes have often been underrepresented in strength and power intervention studies. However, current evidence suggests that when training is scaled and supervised appropriately, women show comparable relative improvements [1, 6, 15, 39]. Neuromuscular characteristics that differ by sex, such as frontal-plane control during landings and directional cuts, can be improved through targeted NMT. These changes are reflected in movement quality and markers linked to injury risk within standard training cycles [13, 46]. In women's football, programs that combine plyometrics with sprint and balance work have led to improvements in multiple areas. These include speed, jumping, balance, and COD ability, provided that progression and technical feedback are maintained throughout. The present results are consistent with these findings [15, 16].

This study has several strengths that support the interpretation of its findings. Participants were randomly assigned to groups using concealed sequence generation, which helped reduce selection bias. Testing procedures were matched by time of day, and assessors were blinded to group allocation. These steps helped limit measurement error and increase objectivity in test outcomes [47]. A familiarization session was conducted before baseline testing. This reduced the risk of learning effects in field-based measures that are known to be sensitive to repeated exposure [48]. The statistical approach followed current guidelines. Data were tested for normality, and both within-group and between-group changes were analyzed. Effect sizes were reported using standardized metrics. These practices are recommended in studies evaluating training interventions [49, 50]. The use of multiple outcome variables such as sprint speed, jumping, change-of-direction, and dynamic balance allowed a more comprehensive assessment of neuromuscular adaptations. Relying on diverse indicators reduces the risk of overinterpreting isolated effects [6, 8, 38]. Finally, correlation analyses were used to examine the relationships between improvements in different domains. This helped clarify how motor qualities may develop together under an integrated training stimulus [2, 4, 26].

The current results across sprinting, horizontal power, change-of-direction speed, and dynamic balance are consistent with existing findings on neuromuscular training. Improvements were observed in domains that depend on stretch-shortening cycle function, braking and re-acceleration capacity, horizontal force direction, and control of trunk and pelvis. The combination of within-group improvements, adjusted between-group differences, and correlations between performance variables suggests that the intervention influenced neuromechanical function on a broad scale. These effects go beyond isolated skill gains and indicate systemic adaptation [7, 24, 38, 40, 42]. Among female university footballers, the results support earlier studies showing that well-structured and supervised neuromuscular training can lead to consistent improvements within short time frames. These adaptations are possible even in already trained athletes [10, 11, 15, 16, 22]. Our findings also agree with broader research on integrated training methods. For example, Choudhary et al. found that complex training improved sprinting, jumping, and change-of-direction performance. This suggests that despite different program structures, both approaches may rely on shared neuromuscular mechanisms [51].

Despite these limitations, the current findings contribute valuable evidence to the growing literature supporting neuromuscular training as a practical and effective method for improving physical performance in female football players. The study specifically targeted university-level athletes, a group that continues to be underrepresented in sports science research despite their increasing involvement in competitive sport. By assessing sprint speed, horizontal power, change-of-direction ability, and dynamic balance within a single training framework, the study provides a multidimensional perspective on functional performance development. Moreover, embedding the program within the athletes' regular training routine enhances ecological validity and demonstrates the feasibility of implementation in real-world settings. The consistent improvements observed across multiple domains suggest that well-structured neuromuscular training can be a valuable component of performance enhancement strategies in women's football.

Study Limitations

This study has several limitations that should be considered when interpreting the results. The relatively small sample size limits the generalizability of the findings, although statistical power was sufficient to detect large effects across all measured outcomes. The eight-week duration primarily reflects short-term neuromuscular adaptations and does not provide information about long-term structural changes or retention. Only field-based performance tests were used, without the inclusion of advanced biomechanical or electrophysiological measures such as electromyography or motion analysis. Potential confounding factors such as nutritional intake, sleep quality, and psychological stress were not strictly controlled. Additionally, the study included only female university football players aged 20 to 24 years, which limits the applicability of the results to other age groups or competitive levels. While all participants were post-pubertal, biological maturity was not objectively assessed, which may be relevant in future studies involving adolescent athletes. Finally, follow-up testing was not conducted, so the sustainability of performance improvements remains unknown.

Conclusions

Neuromuscular training that combines plyometric, sprint, change-of-direction, and balance exercises within a structured framework can contribute to the development of key athletic capacities in female university football players. When integrated into regular team practice and delivered with appropriate progression and supervision, such training facilitates improvements across multiple movement domains. The observed associations between gains in balance, sprinting, and directional change underscore the interdependence of neuromechanical functions and highlight the relevance of integrated training strategies in applied sport settings.

These findings emphasize the potential of neuromuscular training to enhance physical preparedness in female athletes and support its inclusion in routine football conditioning programs.

Conflict of Interest

The authors declare no potential conflicts of interest.

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ORIGINAL ARTICLE

Evaluating the effect of a 12-session Tabata training program on VO_2max and body composition in female workers: a randomized controlled trial

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Abstract

Background and Study Aim Aerobic fitness (VO_2max) and optimal body composition are key components of health and work capacity in adult populations. Among female workers, sedentary lifestyles and poor body composition are commonly associated with reduced aerobic performance, increased obesity, and elevated cardiometabolic risk. Despite the use of various exercise interventions, their relative effectiveness in improving VO_2max and body composition in this specific group remains a subject of practical interest. This study investigated the impact of a four-week Tabata-based HIIT program on VO_2max and body composition in female workers.

Material and Methods A randomized controlled trial was conducted with twenty female workers (mean age 35.1 ± 9.4 years) from Grit Fitness Center. Participants were divided into two groups. Ten women in the experimental group performed Tabata-based HIIT three times per week for four weeks. Ten women in the control group continued their usual routines without exercise. Aerobic capacity (VO_2max) was assessed using the Multistage Fitness Test, which involved shuttle runs at increasing speeds. Body composition was measured with the OMRON HBF-375 bioelectrical impedance analyzer, which estimates fat percentage using small electrical currents. Statistical analysis included paired and independent t-tests with a significance level of $p < 0.05$.

Results After the intervention, the experimental group showed significantly higher VO_2max levels compared to the control group ($t(18) = 2.665$, $p = 0.016$). Significant reductions were also observed in whole-body fat ($t(18) = -5.404$, $p < 0.001$), trunk fat ($t(18) = -4.203$, $p < 0.001$), arm fat ($t(18) = -6.691$, $p < 0.001$), total fat percentage ($t(18) = -2.753$, $p = 0.013$), and BMI ($t(18) = -4.909$, $p < 0.001$). No significant changes were found in visceral fat, resting metabolism, or leg composition ($p > 0.05$).

Conclusions A short Tabata-based HIIT program can improve VO_2max and reduce body fat in female workers. This approach may be effective for promoting workplace health.

Keywords: aerobic capacity, body fat distribution, female workers, high-intensity interval training, workplace wellness.

Introduction

In recent years, workplace health promotion programs have increasingly incorporated time-efficient exercise interventions to counter sedentary behavior among employees. Research findings show that female employees experience higher rates of physical inactivity and body fat accumulation, which negatively affect their body composition and aerobic capacity (VO_2max) [1, 2]. The combination of time constraints, sedentary work routines, and psychological stress among female workers leads to decreased muscle mass and reduced cardiovascular fitness [3]. Body fat levels directly influence VO_2max, while skeletal muscle mass determines oxygen uptake and endurance performance [4, 5]. Maintaining optimal body composition and aerobic capacity serves two critical functions: it supports work performance and helps prevent future cardiometabolic diseases.

Female employees in administrative and service roles spend most of their time sitting and performing mentally demanding tasks without access to structured physical exercise [6]. This work environment contributes to body fat accumulation and reduced aerobic capacity (VO_2max), resulting in lower metabolic performance and decreased work ability [7]. The body requires a balanced distribution of fat and lean mass to maintain musculoskeletal stability, prevent obesity-related health problems, and support posture and daily energy needs. Workers with higher VO_2max levels show greater endurance in daily tasks, reduced fatigue, and improved cardiovascular health,

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which enhances concentration and productivity [1, 8]. Improvements in body fat levels and aerobic capacity directly influence workplace wellness, functional independence, and long-term health. For women balancing professional and personal responsibilities, Tabata-based high-intensity interval training (HIIT) offers an efficient exercise strategy to improve physical fitness.

Poor body composition, marked by high fat levels and low lean mass, increases the risk of obesity and metabolic syndrome and accelerates the aging process [9]. VO_2max is a key indicator of the body's ability to transport and utilize oxygen during physical activity. Studies show that women with lower VO_2max levels tend to have poorer cardiovascular health and reduced work capacity [10]. Improving VO_2max and body composition is essential for female workers to enhance functional ability, delay age-related decline, and improve overall health.

Recent studies have investigated the effects of high-intensity interval training (HIIT), particularly Tabata protocols, on cardiorespiratory and metabolic outcomes in various groups, including inactive women, freestyle wrestlers, and student-athletes participating in virtual reality-based Tabata training [11, 12, 13]. These studies reported positive changes in body composition, aerobic fitness, and mental health. The Tabata HIIT protocol involves 20 seconds of maximal effort followed by 10 seconds of rest, repeated in multiple rounds during a short exercise session. This approach has been shown to significantly improve VO_2max and reduce body fat in young female participants [14].

A meta-analysis by Milanović et al. showed that HIIT methods lead to greater improvements in VO_2max compared to traditional endurance training when participants exercise at 80% of their maximum heart rate or higher [15]. Keating et al. found that interval training reduced body fat more effectively than moderate-intensity continuous training (MICT), while requiring less time and producing better metabolic outcomes [16]. Sooryajith et al. examined the effects of a 12-week Tabata-based HIIT program on sedentary female university students. Participants lost 1.6 kg/m^2 of body mass, reduced their waist-to-hip ratio by 5.45 cm, and lowered body fat percentage by 4.1%, while also improving endurance, agility, and leg strength [17]. These findings suggest that Tabata-based training offers women an effective way to improve physical fitness and body composition through short, equipment-free workouts. Evidence also indicates that Tabata protocols enhance aerobic performance and metabolic function by increasing post-exercise oxygen consumption and activating both aerobic and anaerobic pathways [18, 19].

Analysis of research findings has shown that high-intensity interval training, including Tabata protocols, can produce measurable improvements in VO_2max and body fat reduction across various populations. Researchers emphasize that these physiological adaptations are closely linked to enhanced work capacity, metabolic efficiency, and health-related quality of life in physically inactive individuals. While existing studies demonstrate the general effectiveness of such interventions, their specific application in occupational contexts, particularly among time-constrained female workers, continues to present practical and methodological challenges. This gap limits the ability to develop targeted and time-efficient exercise strategies for improving fitness within real-world work environments.

Although previous studies have examined the effects of Tabata or HIIT in adolescents, obese women, and athletes, the specific impact of this protocol on adult female workers with limited time for exercise has not been clearly established. Therefore, the aim of this study is to evaluate the impact of a four-week Tabata-based HIIT program on VO_2max and body composition in female workers.

Materials and Methods

Participants

This study recruited twenty female office workers aged 19 to 59 years, employed in administrative, cashier, or teaching positions within sedentary occupational settings. These individuals typically engaged in low-activity, desk-based tasks for approximately eight hours per day and had limited access to structured physical exercise.

Eligibility criteria were as follows: (1) no diagnosed cardiovascular or musculoskeletal disorders; (2) no participation in regular exercise programs; and (3) willingness to attend all intervention sessions and complete all required assessments. All participants received written information about the study and provided written informed consent.

At baseline, the physical characteristics of the experimental and control groups were comparable. The mean participant age was approximately 32 years, and average body mass index (BMI) values ranged from normal to slightly overweight. No significant differences were found between groups in height, body weight, or baseline VO_2max, indicating successful randomization. Most participants were office-based and reported sedentary work activity patterns. Baseline physical characteristics are summarized in Table 1.

Ethical Approval

This study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki and was approved by the Ethics Committee of Universitas Negeri Malang (Protocol No. 14.10.02/UN32.14.2.8/LT/2025).

Research Design

The study used a randomized controlled trial (RCT) with two parallel groups: an experimental group (Tabata-based high-intensity interval training, HIIT) and a control group (normal daily activities). Randomization was conducted by an independent researcher using a computer-generated random sequence (1:1). Allocation was concealed in opaque sealed envelopes. A single-blind design was applied. The assessors were unaware of the participants' group assignments to reduce bias (Figure 1).

Training Intervention

The Tabata-based exercise program was conducted over four weeks and included 12 supervised training sessions. Sessions were held three times per week, on Mondays, Wednesdays, and Fridays from 4:00 to 5:00 p.m. Each session lasted approximately 40 minutes and consisted of three phases:

1. Warm-up (8–10 minutes): This phase included dynamic mobility drills and low-intensity resistance exercises using SMARTBANDs or light barbells (2–4 kg, approximately 30–40% of estimated 1RM). Exercises such as shoulder rotations, squat push–pulls, and reverse fly were used to activate major muscle groups and increase heart rate.
2. Main Tabata Session (20 minutes): This phase consisted of 3 to 4 Tabata sets. Each set included eight cycles of 20 seconds of high-intensity effort followed by 10 seconds of rest, following the original Tabata protocol. Functional strength exercises included barbell squats, loaded lunges, high pulls, wide rows, and Copenhagen planks.

a. Intensity Monitoring: Exercise intensity

Table 1. Baseline physical characteristics of participants (mean ± SD)

Variable	Experimental Group (N = 10)	Control Group (N = 10)	p-value
Age (years)	31.7 ± 6.6	38.5 ± 10.8	0.110
Height (cm)	159.35 ± 3.60	154.3 ± 7.86	0.124
Weight (kg)	71.99 ± 14.49	68.62 ± 14.48	0.610
BMI (kg/m²)	28.85 ± 6.21	29.66 ± 4.77	0.577

*p is significant at < 0.05

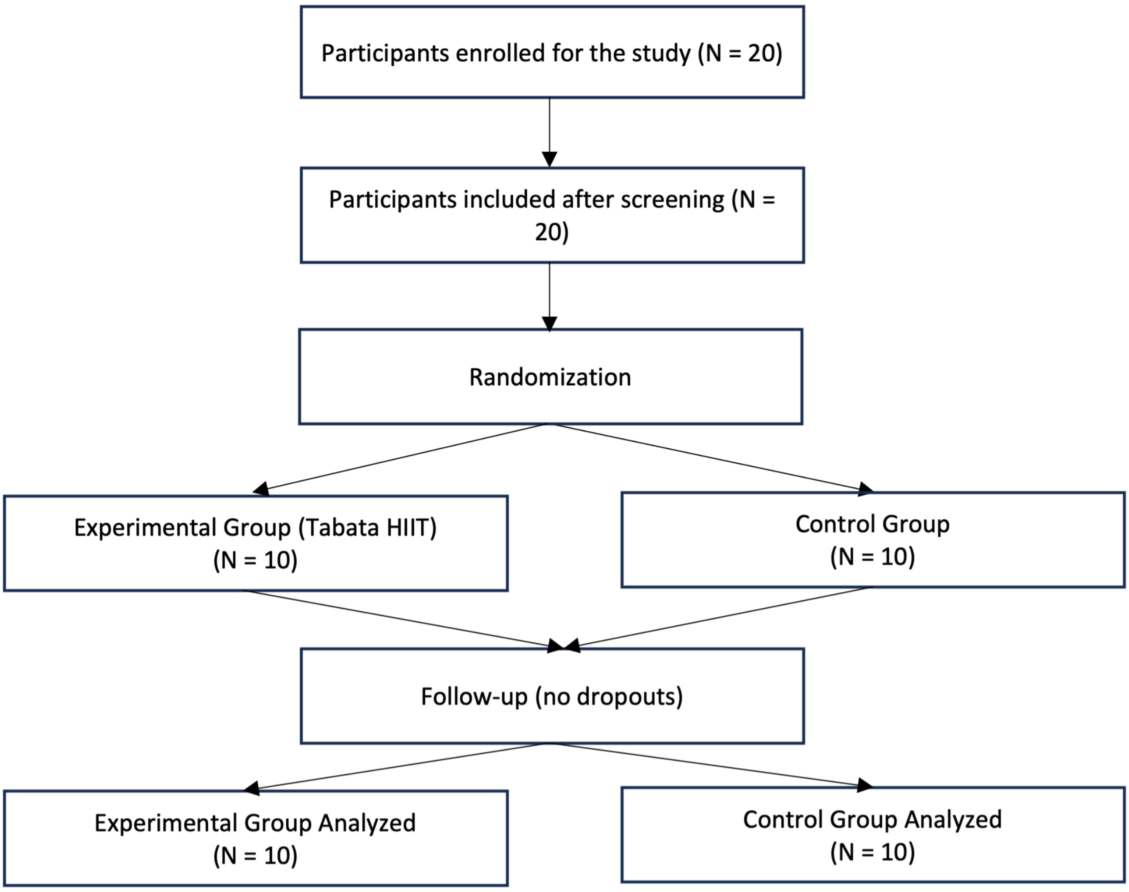

Figure 1. CONSORT flow diagram of participant recruitment, randomization, and analysis

was maintained at 70–85% of HRmax. Heart rate was tracked using a Polar H10 sensor and confirmed using Borg's Rating of Perceived Exertion (RPE 14–16).

b. Progression Strategy: A two-minute passive recovery was provided between sets. Load, tempo, and movement complexity increased each week. For example, Week 1 focused on technique with lighter resistance. Week 4 included complex multi-joint movements at a higher tempo. A summary of the weekly program structure is presented in Table 2.

3. Cool-down (8–10 minutes): This phase involved

Table 2. Four-Week Functional Strength Training Schedule

Week/Session	Training Component	Time / Tempo	Detailed Program
Week 1 – Session 1	Resisted Warm-Up	0:45 each exercise	Shoulder Rotations, Squat + Reverse Fly, Backward-Stepping Lunge L+R + Push Pull, Deadlift + Reverse Fly. Equipment: SMARTBAND + medium–heavy barbell.
	Supersets 1 (Lower Body Focus)	0:30–0:45 / (3)-0-1-0, (1)-H1-X-0	Barbell Front Squat, Offset Loaded Squat with Single-Arm Shoulder Press L/R, Barbell Back Squat, Offset Suitcase Swing Catch L/R. Recovery 0:20 between exercises.
Week 1 – Session 2	Resisted Warm-Up + Supersets 1	25–30 min total	Repeat Session 1 with focus on form and progressive overload. Option to add weight plates.
Week 1 – Session 3	Supersets 1 (Lower Body Focus)	30 min	Repeat with increased intensity, optional heavier barbell. Focus on technique consistency.
Week 2 – Session 1	Supersets 1 (Lower Body Focus)	0:45 each exercise / (3)-0-1-0	Barbell Front Squat, Offset Loaded Squat with Shoulder Press, Barbell Back Squat, Suitcase Swing Catch + Knee Lift L/R.
	Supersets 2 (Upper Body Focus)	0:30–0:45 / (P1)-H1-X-0	Barbell High Pull, Squat Double Pulse Plate Snatch L/R, Barbell Wide Row, Sumo Squat to Lateral Lunge + Arm Reverse Fly. Recovery 0:20 between exercises.
Week 2 – Session 2	Supersets 2 (Upper Body Focus)	30 min	Maintain tempo 3-0-(1)-0. Option to use SMARTBAND or medium-heavy barbell.
Week 2 – Session 3	Supersets 1 + 2 (Full Body Integration)	35 min	Combine key movements from both supersets. Focus on control and range of motion.
Week 3 – Session 1	Supersets 2 (Upper Body Focus)	0:30–0:45 / (P1)-H1-X-0	Barbell High Pull, Squat Double Pulse Single-Arm Plate Snatch + Knee Lift, Barbell Wide Row, Sumo Squat to Lateral Lunge + Arm Reverse Fly.
	Supersets 3 (Lower Body Focus + Core)	0:30–0:45 / 1-(H1)-X-0	Barbell Lunge L/R, Lunge Knee Lift + Suitcase Swing Catch, Copenhagen Plank (Front + Back) with Plate Hold or Powell Arm.
Week 3 – Session 2	Supersets 3 (Lower Body + Core)	30 min	Alternate L/R sides each set. Focus on balance and stability.
Week 3 – Session 3	Supersets 2 + 3 (Upper + Core Focus)	35–40 min	Combine upper body pull/push with lower body + core stabilization drills.
Week 4 – Session 1	Supersets 3 (Lower Body + Core)	0:30–0:45 / varied tempo	Lunge Knee Lift with Suitcase Swing Catch, Copenhagen Plank + Plate Hold, Barbell Lunge L/R. Recovery 0:20–0:30 between exercises.
Week 4 – Session 2	Full Circuit (Superset 1–3 Combo)	40 min	Sequence: Warm-up → Superset 1 → Superset 2 → Superset 3. Perform 2 sets each, 10–15 sec rest.
Week 4 – Session 3	Stretch & Cool Down	10–15 min	Static and dynamic stretching: hamstrings, quads, chest, shoulders, back. Focus on breathing and recovery.

static and dynamic stretching targeting the major muscle groups used during the main session.

Participant compliance was monitored through attendance logs and session-by-session recordings of heart rate and perceived exertion, with an overall attendance rate exceeding 85%.

Control Group

Participants in the control group were instructed to maintain their usual daily routines and to avoid any structured exercise throughout the four-week study period. Compliance was monitored using the International Physical Activity Questionnaire–Short Form (IPAQ-SF), which participants completed weekly to record daily activity levels. This method was used to control for potential bias caused by unplanned changes in physical activity outside the intervention period.

Procedure

The study was carried out in three phases: baseline assessment (pre-test), intervention, and post-intervention assessment (post-test). An initial orientation session was held to explain testing procedures and safety instructions in detail. Baseline measurements of body composition and aerobic capacity (VO_2max) were taken in a controlled laboratory setting before randomization.

After group allocation, the intervention group completed 12 supervised Tabata-based HIIT sessions over four weeks. The control group continued their regular daily routines. At the end of the intervention, both groups completed post-test assessments under the same standardized conditions as at baseline.

All measurements were conducted by three trained assessors who were blinded to group assignment. Assessors completed a two-week training program to ensure inter-rater reliability and adherence to standardized protocols for the OMRON HBF-375 body composition analysis and the Multistage Fitness Test (MFT).

Aerobic Capacity Assessment

Aerobic capacity (VO_2max) was estimated using the 20-meter Multistage Fitness Test (MFT). The test was conducted indoors on a smooth, non-slippery floor at a controlled temperature of 24–26°C. Participants ran back and forth between two lines, 20 meters apart, in time with pre-recorded audio signals that increased in frequency at regular intervals. The test ended when a participant failed to reach the line twice in a row or chose to stop due to fatigue. VO_2max values were calculated using the Leger–Lambert formula [20]. The MFT shows high criterion validity ($r = 0.92$) compared to direct gas analysis and excellent test–retest reliability ($r = 0.95$).

To ensure consistency between pre- and post-test assessments, all tests were administered by the same trained assessors under identical environmental conditions. A 10-minute dynamic warm-up was completed before each test. Standardized verbal encouragement was used to support maximal effort throughout.

Body Composition Assessment

All body composition assessments were conducted in a controlled environment at the indoor Grit Fitness Studio. Participants were instructed to arrive at 9:00 a.m. wearing light athletic clothing and no shoes. They were asked to avoid food, caffeine, alcohol, and strenuous exercise for 12 hours before testing to ensure accurate and consistent results. Detailed instructions were provided before each assessment.

Body composition was measured using the OMRON HBF-375 digital bioelectrical impedance analyzer (Omron Healthcare Co., Kyoto, Japan). Bioelectrical impedance analysis (BIA) is a widely used, non-invasive, and reproducible method for assessing fat mass and fat-free mass in healthy adults. Validation studies have shown acceptable agreement between commercial BIA devices, including Omron models, and reference methods, although accuracy may vary across devices and populations [21].

The following measurements were recorded during the assessment:

a. Subcutaneous fat percentage for the whole body, along with specific values for the trunk, arms, and legs, to assess fat distribution.
b. Skeletal muscle percentage for the whole body and segmented measurements for the trunk, arms, and legs to examine muscle distribution.

Height was measured using a stadiometer with 0.1 cm precision. Body weight was recorded automatically by the OMRON HBF-375 scale. Participants stood upright, barefoot, and held the device electrodes lightly with both hands, following the manufacturer's protocol.

The assessment was conducted in a temperature-controlled indoor environment (24–26°C) to maintain consistency. Each participant completed two measurements. The average of the two was used for data analysis.

All tests were performed by trained assessors who followed the manufacturer's instructions to ensure accuracy and consistency.

Statistical Analysis

All statistical analyses were conducted using JASP software (version 0.18.0; University of Amsterdam, The Netherlands). Data normality was tested using the Shapiro–Wilk test. All variables were normally distributed ($p > 0.05$). Baseline differences between the experimental and control groups were analyzed using independent samples t-tests. Within-group changes from pre- to post-intervention were examined using paired samples t-tests. Between-group differences over time were evaluated with a two-way mixed-design ANOVA (Group × Time) to assess the interaction effect of the Tabata-based HIIT program. Effect sizes (Cohen's d) were calculated using the pooled standard deviation. The effect magnitude was classified as small (d = 0.2), medium (d = 0.5), or large (d ≥ 0.8). Pairwise deletion was used for missing data. Outliers were identified through visual inspection and statistical outlier tests. Statistical significance was set at $p < 0.05$. All results are reported with 95% confidence intervals.

Results

A comparative analysis of baseline body composition and physiological variables was conducted between the experimental and control groups to ensure initial equivalence before the intervention. As shown in Table 3, no statistically significant differences were found between the groups in height, weight, BMI, VO_2max, or other key parameters, with the exception of arm fat percentage, which showed a significant difference ($p < 0.05$).

The independent samples t-test results from Table 3 showed no statistically significant differences between the experimental and control groups for any of the pretest variables ($p > 0.05$). This confirmed their initial comparability. There were no significant differences in height, weight, VO_2max, BMI, body fat percentage, resting metabolism, or most body composition indicators. The groups also showed no statistically significant differences in

Table 3. Baseline comparison of body composition and physiological variables between the experimental and control groups of female workers

Variables	Group	Mean	SD	t-test	p	Mean Difference	Cohen's d	Levene's Test F	Levene's Test p
Height (cm)	Experiment Control	159.45 154.40	3.69 7.85	1.842	0.082	5.05	-0.890	1.713	0.207
Weight (kg)	Experiment Control	71.8 69.0	14.71 14.73	0.425	0.676	2.8	-0.890	0.089	0.768
VO_2max (ml/kg/min)	Experiment Control	23.30 22.55	3.70 2.82	2.938	0.009*	0.75	1.192	0.542	0.471
BMI (kg/m^2)	Experiment Control	28.18 30.25	5.91 4.80	-0.859	0.401	-2.07	-2.195	0.153	0.700
Body Age (year)	Experiment Control	47.7 54.4	11.31 11.74	-1.229	0.210	-6.7	-0.392	0.346	0.564
FAT (%)	Experiment Control	32.33 36.47	4.83 4.48	-1.988	0.620	-4.14	-1.231	0.196	0.664
RM (kcal/day)	Experiment Control	1,448.1 1,439.4	221.17 225.36	0.087	0.932	8.7	-0.157	0.305	0.587
Subcutaneous Fat									
Whole Body (%)	Experiment Control	21.19 33.86	8.13 5.10	-5.636	0.001*	-12.67	-2.417	1.110	0.306
Trunk (%)	Experiment Control	27.96 29.76	6.44 5.11	-6.760	0.001*	-1.8	-1.880	4.209	0.055
Arm (%)	Experiment Control	23.45 48.35	4.94 5.13	-11.056	0.001*	-24.9	-2.992	0.016	0.900
Leg (%)	Experiment Control	38.13 45.50	2.19 6.13	-0.677	0.507	-7.37	-0.392	1.615	0.220
Skeletal Muscle									
Whole Body (%)	Experiment Control	24.57 33.86	2.04 5.10	1.174	0.256	-9.29	0.079	0.230	0.638
Trunk (%)	Experiment Control	18.22 30.86	2.57 3.59	1.004	0.329	-12.64	-0.195	1.018	0.326
Arm (%)	Experiment Control	23.45 48.35	4.94 5.13	0.444	0.662	-24.9	-0.233	0.452	0.510
Leg (%)	Experiment Control	43.11 45.50	9.33 6.13	0.522	0.608	-2.39	-0.602	0.151	0.703

Note: BMI – Body Mass Index; FAT – Body Fat Percentage; RM – Resting Metabolism.; p is significant at < 0.05* segmental fat and muscle distribution, although minor variations were observed. Levene's test results indicated homogeneity of variance across all variables ($p > 0.05$). This confirms that both groups were statistically equal at baseline. Therefore, the post-intervention changes can be attributed to the Tabata-based HIIT intervention rather than to pre-existing differences.

Post-intervention comparisons were conducted to evaluate differences in physiological and body composition outcomes between the experimental and control groups. As shown in Table 4, statistically significant improvements were observed in the experimental group for VO_2max and several fat-related measures, particularly in whole-body fat, trunk fat, and arm fat percentages ($p < 0.05$). These results suggest a favorable effect of the Tabata-based HIIT intervention on aerobic capacity and subcutaneous fat distribution among female workers.

The independent samples t-test results presented in Table 4 showed several statistically significant differences between the experimental and control groups after the four-week intervention. The Tabata HIIT group demonstrated greater improvements in VO_2max ($t(18) = 2.938$, $p = 0.009$, $d = 1.19$) and notable reductions in body fat indicators. These included subcutaneous fat in the whole body, trunk, and arms, as well as total fat percentage and BMI ($p < 0.05$, $d = 1.23–2.99$).

All variables satisfied the assumption of equal variances based on Levene's test ($p > 0.05$). These results indicate large to very large effect sizes in favor of the Tabata group. The findings support the

Table 4. Comparison of post-intervention body composition and physiological variables between the experimental and control groups (mean ± SD, Cohen's d)

Variables	Group	Mean	SD	t-test	p	Mean Difference	Cohen's d	Levene's Test F	Levene's Test p
Height (cm)	Experiment Control	159.45 154.40	3.69 7.85	1.842	0.082	5.05	-0.890	1.713	0.207
Weight (kg)	Experiment Control	71.8 69.0	14.71 14.73	0.425	0.676	2.8	-0.890	0.089	0.768
VO_2max (ml/kg/min)	Experiment Control	23.30 22.55	3.70 2.82	2.938	0.009*	0.75	1.192	0.542	0.471
BMI (kg/m^2)	Experiment Control	28.18 30.25	5.91 4.80	-0.859	0.401	-2.07	-2.195	0.153	0.700
Body Age (year)	Experiment Control	47.7 54.4	11.31 11.74	-1.229	0.210	-6.7	-0.392	0.346	0.564
FAT (%)	Experiment Control	32.33 36.47	4.83 4.48	-1.988	0.620	-4.14	-1.231	0.196	0.664
RM (kcal/day)	Experiment Control	1,448.1 1,439.4	221.17 225.36	0.087	0.932	8.7	-0.157	0.305	0.587
Subcutaneous Fat									
Whole Body (%)	Experiment Control	21.19 33.86	8.13 5.10	-5.636	0.001*	-12.67	-2.417	1.110	0.306
Trunk (%)	Experiment Control	27.96 29.76	6.44 5.11	-6.760	0.001*	-1.8	-1.880	4.209	0.055
Arm (%)	Experiment Control	23.45 48.35	4.94 5.13	-11.056	0.001*	-24.9	-2.992	0.016	0.900
Leg (%)	Experiment Control	38.13 45.50	2.19 6.13	-0.677	0.507	-7.37	-0.392	1.615	0.220
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Arm (%)	Experiment Control	23.45 48.35	4.94 5.13	0.444	0.662	-24.9	-0.233	0.452	0.510
Leg (%)	Experiment Control	43.11 45.50	9.33 6.13	0.522	0.608	-2.39	-0.602	0.151	0.703

Note: BMI – Body Mass Index; FAT – Body Fat Percentage; RM – Resting Metabolism. p is significant at < 0.05* effectiveness of short-term high-intensity interval training in improving aerobic capacity and reducing body fat among female workers.

To evaluate the intervention's effectiveness more precisely, gain scores (pre- to post-test differences) were compared between the experimental and control groups. As shown in Table 5, statistically significant group differences were observed in several key variables, particularly those related to fat distribution and aerobic capacity.

As shown in Table 5, the experimental group demonstrated significantly greater improvements in aerobic capacity and body composition compared to the control group. Participants in the Tabata HIIT group experienced increased VO_2max, along with reductions in whole-body fat, trunk fat, arm fat, total fat percentage, and BMI. These findings suggest that the four-week Tabata HIIT intervention improved both aerobic performance and fat-related body composition parameters among female workers. No statistically significant differences were observed for leg composition ($p = 0.392$), resting metabolism ($p = 0.730$), visceral fat ($p = 0.064$), or body age ($p = 0.392$), indicating that these parameters were less responsive to the short-term intervention.

Figure 2 illustrates the mean changes in VO_2max, BMI, total body fat, and regional fat (whole body, trunk, and arm) between the experimental and control groups following the four-week Tabata-based HIIT intervention. Only variables with

Table 5. Comparison of changes (gain scores) in body composition and VO_2max between the experimental and control groups

Variables	t	df	p
Weight (kg)	-1.990	18	.062
VO_2max (ml/kg/min)	2.665	18	.016*
Whole Body (%)	-5.404	18	< .001*
Trunk (%)	-4.203	18	< .001*a
Arm (%)	-6.691	18	< .001*a
Leg (%)	-0.877	18	.392
FAT (%)	-2.753	18	.013*
RM (kcal/day)	-0.350	18	.730
BMI (kg/m^2)	-4.909	18	< .001*
Visceral Fat (%)	-1.972	18	.064
Body Age (year)	-0.876	18	.392
Whole Body (%)	0.177	18	.861
Trunk (%)	-0.435	18	.669
Arm (%)	-0.522	18	.608
Leg (%)	-1.346	18	.195

Note: Student's t-test. *a Brown–Forsythe test was significant ($p < 0.05$), indicating a violation of the equal variance assumption. p is significant at < 0.05*

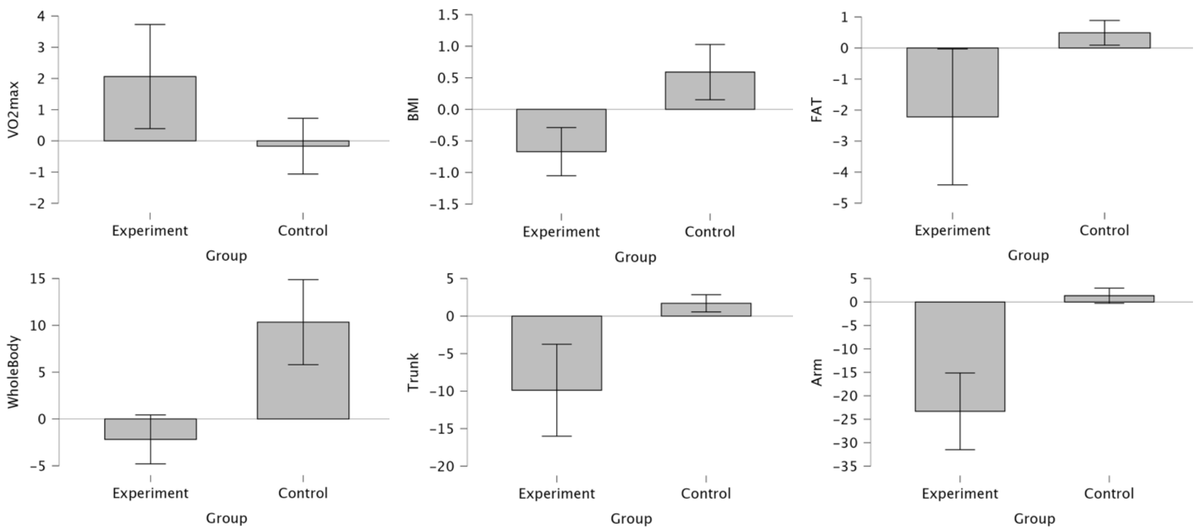

Figure 2. Comparison of mean changes in VO_2max, BMI, total body fat, and regional fat (whole body, trunk, and arm) between the experimental and control groups following the four-week Tabata-based HIIT intervention. Only variables showing statistically significant between-group differences ($p < 0.05$) are presented.

statistically significant between-group differences ($p < 0.05$) are presented.

The four-week Tabata-based HIIT intervention led to significant improvements in aerobic capacity (VO_2max) and reductions in BMI, total body fat, and regional fat in the whole body, trunk, and arms. The experimental group showed greater gains in VO_2max and more pronounced fat loss compared to the control group. Participants in the Tabata group experienced substantial decreases in body fat in all reported regions, accompanied by reductions in BMI, indicating favorable changes in body composition. No significant changes were observed in the control group. These results confirm that Tabata-based HIIT is an effective strategy for improving aerobic fitness and reducing regional body fat over a short intervention period.

Discussion

This study examined the effects of a 12-session Tabata-based high-intensity interval training (HIIT) program conducted over four weeks on VO_2max, body fat, and BMI in female workers. Participants in the intervention group demonstrated greater improvements in VO_2max, along with reductions in body fat, trunk fat, arm fat, total fat percentage, and BMI, compared to the control group.

Research evidence, including a systematic review and meta-analysis, has shown that HIIT significantly improves cardiovascular fitness and body composition, producing greater reductions in body fat and larger gains in VO_2max compared to no exercise or moderate-intensity exercise [22]. The Tabata method induces both anaerobic and aerobic adaptations through its interval structure of 20 seconds of work followed by 10 seconds of rest, as reported in a dedicated review [23]. Studies involving overweight women found that brief HIIT programs increase VO_2max and decrease body fat percentage [24]. Similar results have been observed in elite martial arts athletes, where HIIT was associated with favorable changes in body composition [25]. Another study showed that obese middle-aged women who completed eight weeks of aquatic HIIT improved physical fitness and demonstrated reductions in total cholesterol and interleukin-6 (IL-6) levels, indicating cardiovascular and metabolic benefits [26]. Research on women aged 25–30 found that attending Tabata sessions three times per week promoted fat loss and improvements in muscular strength and endurance [27]. Similarly, Shah et al. [28] reported that Tabata training reduced waist circumference and BMI in women aged 20–35 years. The study found that 20-minute Tabata sessions reached 86% of maximum heart rate and 74% of VO_2max, supporting its role as a time-efficient workout strategy [19].

The Tabata-HIIT protocol enhances VO_2max by increasing maximal cardiac output, stroke volume, and skeletal muscle mitochondrial oxidative capacity. High-intensity exercise intervals stimulate type II muscle fiber activation and mitochondrial growth, which improves oxygen uptake and utilization efficiency [23]. Elevated post-exercise oxygen consumption (EPOC) and a higher metabolic rate during recovery contribute to greater fat oxidation, leading to reductions in total body fat as well as regional fat in the trunk and arms. A meta-analysis reported a significant average weight loss of −1.86 kg (95% CI: −2.55 to −1.18) following HIIT, based on 36 randomized controlled trials [17]. Reductions in central and arm fat are also associated with improvements in BMI and total fat percentage.

This study highlights two key benefits for female workers. First, brief Tabata-HIIT programs deliver measurable health improvements within a limited time frame. Second, such interventions may enhance workplace wellness initiatives by supporting body composition improvements and cardiovascular fitness among employees.

Limitations of the Study

This study faced several limitations. The intervention lasted only four weeks and included a small number of participants from a single workplace. Body composition was assessed using the OMRON Karada Scan HBF-375, a bioelectrical impedance device that is sensitive to hydration levels, which may have introduced measurement error compared to more accurate methods.

In addition, several factors may have influenced internal validity. Dietary intake, occupational physical activity, and sleep patterns were not strictly controlled and could have affected changes in body composition and aerobic capacity. Although attendance was supervised, the quality of adherence, including intensity compliance, may have varied among participants. These limitations should be considered when interpreting the study results.

Future Research Directions

Future studies should extend the intervention period to 8–12 weeks and include larger and more diverse samples of female workers. The use of biochemical markers, such as irisin levels and mitochondrial enzyme activity, would help clarify the physiological mechanisms behind fat loss and improvements in aerobic performance.

Conclusions

This study provides evidence that a short-term Tabata-based high-intensity interval training (HIIT) protocol can significantly improve aerobic capacity and reduce body fat among female workers. After four weeks of supervised training, participants demonstrated increases in VO_2max and decreases in trunk fat, arm fat, and total body fat percentage compared to a control group maintaining usual daily activities.

Despite these promising findings, the short intervention period and small sample size require caution in interpretation. Nevertheless, the Tabata-based HIIT approach appears to be a time-efficient and practical strategy that could be implemented in workplace wellness programs for populations with limited time availability.

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Conflict of Interest

The authors declare no conflicts of interest related to the research, authorship, or publication of this article.

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ORIGINAL ARTICLE

The effect of moderate-intensity combined exercise in decreasing inflammation in young obese women

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

Abstract

Background and Study Aim Obesity results from excessive lipid accumulation in adipose tissue, which causes low-grade inflammatory reactions. These reactions are characterized by the production of pro-inflammatory cytokines. Endurance-resistance combined exercise is believed to inhibit the activation of inflammatory pathways through several mechanisms. The aim of this study was to investigate the impact of endurance-resistance combined exercise on decreasing serum TNF-α and IL-6 levels in young obese women.

Material and Methods A pre–post control group design was used with 16 obese women aged 20–30 years in Malang, Indonesia. Participants were randomly assigned to a control group (CG, n = 8) or a combined exercise group (EXG, n = 8). The combined exercise consisted of 20 sessions of treadmill exercise at 60–70% HRmax and circuit training at 60–70% 1RM intensity, performed over 4 weeks. Pre- and post-exercise blood samples were analyzed to measure serum TNF-α and IL-6 levels using the colorimetric assay method. Statistical analysis included independent and paired t-tests with a 5% significance threshold. Effect size was evaluated using Cohen's d, with d > 0.8 defined as large.

Results Baseline characteristics showed no significant differences between groups. The combined exercise group demonstrated significant reductions in TNF-α (p = 0.010) and IL-6 (p = 0.018) compared to the control group, with large effect sizes for TNF-α (d = 1.23) and IL-6 (d = 1.00).

Conclusions Moderate-intensity combined exercise significantly reduced pro-inflammatory cytokines, including TNF-α and IL-6, compared to the control group. The findings suggest that endurance-resistance combined exercise may serve as an effective therapeutic strategy for inflammatory diseases and can be recommended for obesity treatment.

Keywords: IL-6, TNF-α, combined exercise, obese women, cytokine

Introduction

Obesity represents a complex metabolic condition influenced by genetic, behavioral, and environmental factors. It is closely associated with chronic low-grade inflammation, which contributes to the development of various metabolic and cardiovascular disorders. The excessive accumulation of adipose tissue promotes the secretion of pro-inflammatory cytokines, leading to systemic inflammation and impaired metabolic homeostasis. The growing prevalence of obesity underscores the need to address its physiological consequences and health implications in different populations.

In this context, the incidence of obesity has consistently risen worldwide during recent decades. In 2022, the World Health Organization (WHO) stated that about 16% of people aged 18 years or older were obese, a figure that has doubled since 1990 [1]. The 2023 Indonesian Basic Health Research (Riskesdas) reported that the prevalence

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of obesity among individuals aged over 18 years was 23.4%, an increase from 21.8% in 2018 [2]. The prevalence of obesity among Indonesian women (31.2%) is almost twice that of men (15.7%) [2], which may be attributed to differences in adipose tissue distribution and hormonal influence [3]. Obesity is defined as excessive lipid accumulation that impairs health [1]. The increasing prevalence of obesity is a significant concern for both global and Indonesian public health because it contributes to metabolic disorders such as insulin resistance and cardiovascular disease [4].

The mechanism underlying obesity involves low-grade chronic inflammatory reactions in white adipose tissue (WAT). Hyperplasia and hypertrophy of WAT lead to decreased vascularization and eventually cause tissue necrosis [5]. The human body recognizes this injury and initiates inflammatory reactions. Immune cells involved in the reaction secrete inflammatory mediators, such as cytokines, to amplify the response. Examples of these mediators are tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6) [6]. Furthermore, TNF-α impairs insulin signaling and promotes insulin resistance, contributing to the progression of metabolic syndrome [7]. While TNF-α shows only pro-inflammatory effects, IL-6 may act as both a pro-inflammatory and an anti-inflammatory cytokine, depending on the cell secreting it [6].

There are several modalities to treat obesity, targeting each step of its pathogenesis to either increase energy expenditure or decrease energy input. Physical exercise is known as an anti-obesity therapy that is less invasive while providing optimal results [8]. Exercise is also recognized for its anti-inflammatory effects [9]. The two types of exercise, endurance (aerobic) and resistance (anaerobic), have different mechanisms for reducing inflammation [10]. The WHO recommends that adults perform endurance training for at least 150 minutes per week at moderate intensity or 75 minutes per week at high intensity [11]. For resistance exercise, the American College of Sports Medicine (ACSM) suggests performing 8–10 sets weekly for different muscle groups, with each set containing 8–12 repetitions [11]. Among various exercise intensities, moderate intensity is recommended for reducing inflammation [12]. Combined exercise, which integrates endurance and resistance training in a single session, induces both anti-inflammatory mechanisms and is believed to produce better results in a shorter period [13]. However, previous studies have also shown that endurance exercise alone can reduce inflammation more effectively than combined exercise [9].

Combined exercise has been shown to decrease inflammation by reducing the secretion of pro-inflammatory cytokines. Previous studies that combined endurance exercise with resistance exercise on separate days, using low endurance frequency and moderate resistance frequency, showed significant reductions in TNF-α and IL-6 levels [14]. Meanwhile, the effect of performing endurance-resistance exercise on the same day with high frequency has not been extensively explored, especially regarding pro-inflammatory cytokines in obese women. Several studies have demonstrated that long-term exercise, performed over eight weeks, can significantly decrease pro-inflammatory cytokines [15]. However, evidence on the effects of shorter exercise periods remains limited. One study reported that two weeks of endurance exercise did not significantly reduce IL-6, while another study found increased TNF-α after three weeks of combined exercise [16, 17]. Based on this finding, the minimum duration of exercise required to produce an anti-inflammatory effect remains unclear. A meta-analysis in healthy subjects reported that a significant reduction in TNF-α levels was mainly observed in interventions with high exercise frequency (⩾3 times per week), while a significant reduction in IL-6 was more commonly reported in studies with low exercise frequency (<3 times per week). However, the analysis also showed a high level of heterogeneity among the studies, so the effectiveness of high-frequency exercise in reducing pro-inflammatory cytokines is still not fully understood and requires further investigation [18].

There is limited comparative evidence regarding circulating IL-6 concentrations between Southeast Asian and European women within a single study cohort. South Asian women have elevated circulating IL-6 levels, partly due to greater visceral fat and overall body fat percentages compared with European women [19]. Malay ethnicity, representing Southeast and South Asian populations, shows higher total and visceral adiposity compared to Chinese and Caucasian groups [20]. Therefore, South Asian women are more prone to developing type 2 diabetes than European women, and inflammation plays a central role in the development and progression of this disease [21]. These findings indicate that inflammatory-mediated diseases among Southeast Asian women should be carefully addressed in terms of their pathomechanisms and treatment approaches.

Analysis of research findings has shown that physical exercise, particularly the combination of endurance and resistance training, exerts measurable anti-inflammatory effects and contributes to the regulation of metabolic health in obesity. Researchers emphasize that exercise parameters such as frequency, duration, and intensity may differently influence cytokine responses, yet the physiological outcomes vary across populations and study designs. At the same time, variations in inflammatory markers among women of different ethnic backgrounds, as well as uncertainties regarding the optimal exercise duration and frequency, continue to limit the practical implementation of exercise-based interventions for inflammation control. These considerations define the rationale for further investigation into how specific exercise modalities can modulate inflammatory responses in young obese women.

Although prior research has examined the effects of combined exercise on serum pro-inflammatory markers, the effectiveness of the combination method, exercise duration, and exercise frequency remains controversial. This study aims to investigate the impact of high-frequency, moderate-intensity combined exercise conducted over a four-week period on serum TNF-α and IL-6 levels in young healthy women with obesity, particularly within the Southeast Asian population. We hypothesize that moderate-intensity combined exercise performed five times per week for four weeks will decrease both TNF-α and IL-6 levels compared to the control group.

Materials and Methods

Participants

The sample size was determined using the Higgins and Kleinbaum formula, taking into account a confidence level of 95%, a margin of error of 5%, and an estimated proportion of 0.5. Based on these parameters, a minimum of sixteen participants was required. Sixteen women aged 20–30 years were included in the study. Their body mass index ranged from 25 to 35 kg/m^2 according to the Asia-Pacific criteria, and body fat percentage exceeded 40%, as measured using the Bioelectrical Impedance Analysis method. Participants had normal blood pressure (systolic 121.00 ± 10.64 mmHg, diastolic 72.13 ± 9.19 mmHg), fasting blood glucose, hemoglobin levels, resting heart rate, body temperature, and oxygen saturation. Each participant was medically certified as healthy through a clinical examination and a valid health certificate. None of the participants had a history of chronic illnesses such as heart disease, hypertension, diabetes mellitus, stroke, respiratory problems, cancer, fractures or trauma injuries, or digestive diseases. All were confirmed to have abstained from alcohol consumption, smoking, or any history of alcohol or tobacco use during the past five years.

Participant recruitment was conducted through an online registration form in June 2024 for women in Malang, Indonesia. Participants were selected using a consecutive sampling method and subsequently randomized into two groups: CG (control group; n = 8) and EXG (combined exercise group; n = 8). Randomization was performed using a computer-generated random number sequence. Allocation concealment was ensured through sequentially numbered, opaque, sealed envelopes prepared by an independent researcher who was not involved in participant recruitment or assessment. Due to the nature of the intervention, blinding of participants was not feasible; however, outcome assessors were blinded to group assignments. All study procedures received approval from the Health Research Ethics Commission, Faculty of Medicine, Universitas Airlangga (203/EC/KEPK/FKUA/2025).

Research Design

The endurance-resistance combined exercise program was performed five times weekly (Monday–Thursday and Saturday) over a four-week period for a total of 20 sessions. The exercise sessions were scheduled in the morning (06:00–10:00 a.m.), and both endurance and resistance exercises were completed on the same day. Each session followed a standardized sequence designed to optimize performance and recovery. It consisted of a warm-up, endurance exercise, resistance exercise, and cool-down phase. The warm-up and cool-down phases involved treadmill jogging using a Richter Treadmill. Endurance exercise included treadmill running at a speed of 1.5 mph and 5% inclination, at 60–70% HRmax for 30–40 minutes, measured and monitored with a Polar H7 Heart Rate Sensor. Individual HRmax was estimated using the Haskell and Fox formula (220 - age) [22, 23].

The resistance component followed circuit training that targeted both upper and lower body muscle groups. Exercises for the upper body included chest presses, overhead presses, and lat pull-downs. Exercises for the lower body consisted of hip abductions, leg presses, and leg curls. The intensity of resistance exercise was maintained at 60–70% of one-repetition maximum (1-RM), with four sets of 10–12 repetitions. Each set was followed by 30–60 seconds of active rest, and there was a 3–5 minute active rest between endurance and resistance components. The 1-RM was determined as the maximum amount of weight a participant could lift for one complete repetition of a specific exercise while maintaining proper form. Before testing, participants were provided sufficient rest to ensure optimal condition for the 1-RM test.

All exercise sessions were supervised and conducted by certified personal trainers from Atlas Sports Club Malang, maintaining a trainer-to-participant ratio ranging from 1:1 to 1:3 to ensure proper guidance and adherence to the protocol. Details of the specific endurance-resistance combined exercise program are presented in Table 1. Confounding variables in both groups were monitored using self-report questionnaires requiring participants to report their physical activity and dietary intake.

Data Collection Procedure

Blood samples (3 mL) were collected from the cubital vein before exercise (week 0) and after exercise (week 4). An 8-hour overnight fast was required before blood collection. Samples were centrifuged to separate serum, which was immediately analyzed for serum TNF-α and IL-6 levels using the Human Colorimetric Assay method at the laboratory. TNF-α levels were quantified using a Human TNF-α ELISA Kit (Catalog No. E-EL-H0109; Elabscience Biotechnology Inc., Houston, TX, USA) with a sensitivity of 4.69 pg/mL, a detection range of 7.81–500 pg/mL, and a coefficient of variation of less than 10%. IL-6 levels were measured using a Human IL-6 ELISA Kit (Catalog No. E-EL-H6156; Elabscience Biotechnology Inc., Houston, TX, USA) with a sensitivity of 0.94 pg/mL, a detection range of 1.56–100 pg/mL, and a coefficient of variation of less than 10%. Laboratory personnel who performed the ELISA analyses were blinded to the participant group assignments.

Statistical Analysis

Data analysis was performed using SPSS software version 25. The normality of the dataset was tested with the Shapiro–Wilk test. A paired-sample t-test was used to evaluate changes in cytokine levels (TNF-α and IL-6) within each group, whereas an independent-sample t-test was used for comparisons between groups. Alternatively, the Mann–Whitney U test was used to analyze data that were not normally distributed. Cohen's d was applied to evaluate effect size, with a value of $d > 0.8$ considered large. Analyses were regarded as statistically significant if $p < 0.05$.

Results

The dropout rate in this study was 0%, and the attendance rate was 100%. Baseline analysis revealed no significant differences between the control group (CG) and the exercise group (EXG) ($p > 0.05$), except for oxygen saturation. These results indicate that both groups had comparable baseline profiles, suggesting that the changes in cytokine levels were mainly attributed to the intervention. The results of the characteristics analysis are presented in Table 2.

Table 1. Details of the Combined Endurance-Resistance Training Protocol

Training Session	Combination Training			
	Type	Intensity	Duration or Sets and Reps	Targeted Muscles
1–10	Endurance	60% HRmax	30 minutes	-
	Resistance	60% 1-RM	4 set x 10 reps	Upper and lower extremities
11–20	Endurance	70% HRmax	40 minutes	-
	Resistance	70% 1-RM	4 set x 12 reps	Upper and lower extremities

Table 2. General Characteristics of the Study Subjects (n = 8 per group)

Parameters	Group	Mean ± SD	p-value
Age (years)	CG	23.38 ± 1.92	0.113[a]
	EXG	25.00 ± 1.93	
TDS (mmHg)	CG	124.88 ± 4.05	0.352[a]
	EXG	121.00 ± 10.64	
TDD (mmHg)	CG	72.13 ± 9.19	0.619[a]
	EXG	74.13±6.27	
DJI (bpm)	CG	93.38 ± 8.45	0.290[a]
	EXG	89.25 ± 6.43	
Suhu (°C)	CG	35.15 ± 1.14	0.111[b]
	EXG	35.86 ± 0.43	
GDP (mg/dL)	CG	101.13 ± 14.72	0.604[a]
	EXG	98.25 ± 4.23	
Hb (g/dL)	CG	14.43 ± 1.70	0.537[a]
	EXG	13.95 ± 1.27	
TB (m)	CG	1.56 ± 0.06	0.935[a]
	EXG	1.56 ± 0.06	
BB (kg)	CG	76.13 ± 9.55	0.778[a]
	EXG	77.94 ± 15.09	
BMI (kg/m^2)	CG	30.96 ± 2.91	0.672[a]
	EXG	31.80 ± 4.64	
Fat (%)	CG	46.34 ± 2.34	0.544[a]
	EXG	47.35 ± 3.96	

Note: CG = Control Group; EXG = Combined Exercise Group; SD = Standard Deviation; (a) = Independent t-test; (b) = Mann–Whitney U test; TDS = Systolic Blood Pressure; TDD = Diastolic Blood Pressure; DJI = Resting Heart Rate; GDP = Fasting Blood Glucose; Hb = Hemoglobin; TB = Height; BW = Body Weight; BMI = Body Mass Index.

Table 3. Differences in IL-6 and TNF-α levels before and after exercise in each group (n = 8 per group)

Group	Parameters	Mean ± SD	p-value
Control Group	Pre-exercise IL-6	2.52 ± 1.26	0.165
	Post-exercise IL-6	3.19 ± 1.50	
	Pre-exercise TNF-α	31.25 ± 19.34	0.187
	Post-exercise TNF-α	42.91 ± 23.95	
Combined Exercise Group	Pre-exercise IL-6	2.44 ± 0.87	0.018*
	Post-exercise IL-6	1.62 ± 0.77	
	Pre-exercise TNF-α	44.87 ± 20.43	0.010*
	Post-exercise TNF-α	28.67 ± 16.49	

Note: SD = Standard Deviation; * = statistically significant at $p < 0.05$ (paired-sample t-test).

Table 4. Effect size results for IL-6 and TNF-α levels (n = 8 per group)

Group	Parameters	Cohen's d
Combined Exercise Group	Pre-exercise IL-6	1.002
	Post-exercise IL-6	
	Pre-exercise TNF-α	1.230
	Post-exercise TNF-α	

Note: The effect size is considered large when Cohen's d > 0.8.

The results of cytokine analysis are summarized in Table 3, which presents the differences in IL-6 and TNF-α levels before and after the intervention in both groups.

Following the four-week training program, participants in the combined exercise group showed a clear downward trend in pro-inflammatory cytokine levels, whereas the control group did not exhibit notable changes. This tendency suggests that regular moderate-intensity endurance-resistance exercise contributed to a reduction in systemic inflammation. The results also demonstrate a consistent response pattern for both cytokines, reflecting an overall anti-inflammatory adaptation to the exercise protocol.

The results of the effect size analysis are presented in Table 4, which summarizes the magnitude of changes in IL-6 and TNF-α levels following the four-week combined exercise program.

The data indicate that both cytokines demonstrated large effect sizes, confirming a substantial physiological response to the intervention. These findings emphasize that the applied training protocol was not only statistically effective but also produced a meaningful practical impact on reducing inflammation among participants in the exercise group.

Discussion

This study aimed to examine the impact of moderate-intensity combined exercise on serum TNF-α and IL-6 levels in young healthy obese women. The results showed that a four-week endurance-resistance training program performed five times per week significantly reduced circulating concentrations of both cytokines. This finding suggests that moderate-intensity combined exercise may contribute to reducing inflammatory responses associated with obesity.

These outcomes are consistent with previous research highlighting the anti-inflammatory effects of physical activity. Moderate-intensity endurance-resistance programs have been reported to lower serum TNF-α and IL-6 levels after several weeks of training [14]. Other studies have also demonstrated that physical exercise plays an important role in suppressing pro-inflammatory cytokines and improving metabolic function, thereby contributing to better health outcomes in individuals with obesity [8, 9, 10, 12]. The observed reductions in inflammatory markers in this study align with these findings, reinforcing the evidence that combined exercise can effectively modulate inflammation and promote metabolic balance in overweight populations.

The decrease in serum TNF-α and IL-6 levels induced by endurance and resistance exercise involves different physiological mechanisms. The mechanism of endurance exercise in decreasing inflammation is related to increased insulin sensitivity. Hyperglycemic conditions cause oxidative stress, thereby promoting inflammation. AMP-activated protein kinase (AMPK), activated by insulin, translocates GLUT-4 from the cytosol to the skeletal muscle and adipocyte membranes, allowing more glucose to be taken up from the blood. Resistance exercise acts through a different mechanism, involving the secretion of myokines such as IL-6 by skeletal muscle, which antagonize pro-inflammatory cytokines. In addition, resistance exercise stimulates growth hormone (GH) activity and enhances lipolysis. As a result of the lipolysis process, lipid storage in adipose tissue decreases, as does the inflammatory reaction. Combined exercise integrates both effects within a single training session, achieving more optimal results in a shorter duration.

Being a biphasic cytokine, the mechanism of IL-6 in reducing inflammation is determined by the type and duration of exercise. During acute moderate-intensity exercise, resistance exercise is more effective in increasing serum IL-6 myokines compared with endurance exercise [24]. Myokine IL-6 binds to the mIL6-R/gp130 receptor and activates the phosphoinositide-3-kinase/Akt (PI3K-Akt) pathway. PI3K-Akt signaling activates the mammalian target of rapamycin complex 1 (mTORC1) and enhances glucose uptake. The mTORC1 protein complex induces ribosome biogenesis and increases mRNA translational efficiency, resulting in skeletal muscle hypertrophy [25]. Skeletal muscle hypertrophy increases resting metabolic rate (RMR), which enhances energy expenditure [26]. In turn, chronic moderate-intensity endurance exercise significantly reduces serum IL-6 levels more than resistance exercise [14]. Energy expenditure during moderate-intensity endurance exercise predominantly relies on fatty acid oxidation, with a smaller contribution from glucose oxidation [27]. Fatty acids are obtained through the lipolysis of triacylglycerol, which is dominant in white adipose tissue as the main lipid storage organ [28]. This process reduces the accumulation of adipocyte–macrophage M1 tissue, leading to decreased IL-6 cytokine secretion [14, 29].

Our study demonstrated that combined exercise can significantly reduce inflammation. However, previous comparative studies have reported significant reductions in pro-inflammatory cytokines with other types of exercise. Khalafi et al. conducted a systematic review and meta-analysis indicating that only endurance exercise reduced TNF-α levels [30]. The difference in findings is likely due to variations in participant age, as our study included young adult women (20–30 years old), while Khalafi et al. examined subjects aged 65 years and older. The principle of resistance exercise involves inducing muscle damage to stimulate an acute inflammatory response. With aging, muscle cells undergo degeneration and exhibit inflammatory reactions even without exercise-induced stimulation [31, 32].

Moderate intensity is considered the most optimal level for reducing inflammation. A systematic review by Cerqueira et al. reported increased TNF-α levels only in groups exposed to high-intensity exercise [12]. High-intensity exercise may cause exercise-induced muscle injury due to excessive mechanical stress [33]. Sarcomere overstretching leads to the opening of stretch-activated calcium channels. The resulting calcium influx promotes degradation of contractile proteins, which the body recognizes as tissue injury, thereby initiating inflammatory responses [34].

In summary, the findings of this study confirm that moderate-intensity combined exercise effectively reduces pro-inflammatory cytokines such as TNF-α and IL-6 in young obese women. The results align with previous studies demonstrating that combined endurance-resistance training produces measurable anti-inflammatory effects through mechanisms linked to improved insulin sensitivity, activation of AMPK, and increased myokine secretion. These physiological adaptations jointly contribute to reduced systemic inflammation and enhanced metabolic regulation. Overall, the present study adds to the growing evidence that moderate-intensity combined exercise is an efficient and practical approach to reducing inflammation associated with obesity. The findings support the importance of incorporating both endurance and resistance components into structured training programs to achieve meaningful metabolic and anti-inflammatory benefits within a relatively short intervention period.

Study Limitations

Several limitations in this study should be considered when interpreting the findings. This study did not compare combined exercise with endurance or resistance exercise performed independently. Within the same age group, different exercise modalities can produce different outcomes. Moreover, variations in exercise intensity and duration may influence physiological responses and adaptation; however, these factors were not compared in this research. Future studies should include more diverse interventions, varying in type, intensity, frequency, and duration, to develop comprehensive exercise recommendations for specific age and sex groups.

In addition, several variables other than obesity may affect pro-inflammatory cytokine levels, including dietary intake, stress, smoking habits, menstrual cycle, and medication use. Although controlling all such factors in human studies is challenging, future research should monitor and account for these variables to minimize potential bias.

Conclusions

This study confirms that moderate-intensity combined exercise can be applied as an effective method for controlling inflammation related to obesity in young women. The physiological effects observed during the intervention demonstrate the practical value of combining endurance and resistance elements within a single training program. The results emphasize the importance of structured physical exercise as a component of health management for individuals with obesity.

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Conflict of interests

The authors declare that there is no conflict of interests.

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ORIGINAL ARTICLE

Effects of an 8-week combined jump rope and walking intervention on physical fitness in students with intellectual disabilities

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Abstract

Background and Study Aim Individuals with intellectual disabilities (ID) face obstacles in performing physical activity. This negatively affects their fitness and quality of life. Therefore, training programs for individuals with ID need to be developed. The present study aims to determine the effects of combining step rope jumping and walking.

Material and Methods The study used a two-group pre-test and post-test quasi-experimental design. Thirty students with ID (age = 16.5 ± 1.9 years) participated. They were divided into two groups: an experimental group (n = 15) and a control group (n = 15). The experimental group received an intervention combining step rope jumping and walking. The intensity was 70%–85% of maximum heart rate for 20–30 minutes. The instruments used were sit-and-reach for flexibility, push-ups for chest and arm muscle strength, sit-ups for abdominal strength, back-ups for back strength, and a 1600-meter run/walk for cardiovascular endurance. Data were analyzed using ANCOVA. Assumption testing (normality, homogeneity, and linearity) was conducted before performing ANCOVA.

Results The results show $p < 0.001$; $\eta^2_p > 0.14$; pholm < 0.001, indicating a significant difference between groups with a large effect.

Conclusions An eight-week combined jump rope and walking exercise program for individuals with ID led to improvements in flexibility, chest and arm strength, abdominal and back strength, and cardiovascular endurance. These findings suggest that the intervention can improve physical fitness in this population. The study contributes to knowledge about exercise interventions for individuals with ID. Future research should explore other types of exercise suitable for this group to support their fitness and health.

Keywords: disability exercise, intellectual disability, jump rope step, physical fitness, walking

Introduction

Physical activity contributes to maintaining physical fitness and general well-being, particularly in individuals with developmental conditions. Individuals with intellectual disabilities (ID) often experience challenges in performing physical activities, which may limit their functional capacity and overall health. Although various exercise programs are applied in this population, their relative effectiveness in improving specific components of physical fitness remains a subject of practical interest. The present study aims to determine the effects of combining step rope jumping and walking.

In context, Individuals with intellectual disabilities (ID) often experience reduced levels of physical activity compared to the general population. As a result, they face increased risk of walking difficulties, impaired balance, and various health conditions [1, 2]. These include a higher prevalence of obesity, multimorbidity, and metabolic syndrome, along with more sedentary behavior in adulthood [3, 4]. One approach to improving mobility in individuals with ID is the introduction of structured motor skill tasks [5]. Gradual increases in physical activity can help reduce sedentary patterns and support functional health. Enhancing physical activity in this population is associated with improvements in fitness, daily functioning, and overall well-being [6, 7, 8]. Since physical fitness influences both productivity and health status [9, 10], regular engagement in physical activity is considered a necessary part of health maintenance and daily performance [11].

Academics have made efforts to provide recommendations for safe physical activities to improve the fitness of people with intellectual disabilities. Yoga has been shown to improve balance, anthropometric parameters, and lung function in individuals with intellectual disabilities (ID) [12]. Strengthening and aerobic exercises given to students with intellectual disabilities have benefits for walking ability, balance, and functional independence [13]. Recreational activities are beneficial and provide health benefits for people with intellectual disabilities [14]. Traditional sports games are considered suitable recreational options for people with intellectual disabilities [15]. Physical

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activity in the form of exercise can also improve cognitive abilities in people with disabilities [4]. Several exercise programs tested in previous studies have provided benefits in improving the fitness of students with ID. However, trials of other exercise models need to be conducted to increase the variety of options for people with ID. A range of exercise models can offer alternatives for developing motor skills and physical fitness.

Other exercise models such as jump rope have benefits for developing coordination, strength, agility, and cardiovascular endurance in non-disabled individuals [16]. These benefits may also apply to people with disabilities, once the activity is adapted to inclusive criteria. Jumping rope is a complex movement that requires multisensory coordination, balance, and synchronized movement rhythm [17]. Exercise models that support coordination and balance can help improve both physical fitness and motor skills in students with ID. Meanwhile, other models such as walking are simpler and can improve physical ability and body mass index (BMI) [18, 19]. Combining complex and simple exercise types is one way to make complex activities more manageable for students with ID. Alternating between simple and complex tasks allows rest periods and reduces fatigue caused by repetitive movements. Exercise models for students with ID must take their specific characteristics into account. This helps to achieve training goals and reduce the risk of injury [20]. People with disabilities face higher injury risks due to low strength and balance. For this reason, exercise programs should consider the needs and limitations of this population [21].

Providing exercise programs and using fitness equipment for people with disabilities requires further exploration to ensure safety [2]. Interventions for people with disabilities also require caution [22]. This is due to the limited availability of literature on exercise programs and related equipment for individuals with intellectual disabilities [23].

Analysis of research findings has shown that various physical activity programs can support the development of motor skills, physical fitness, and cognitive functioning in individuals with intellectual disabilities. Researchers emphasize that combining structured and adaptive exercise types may offer additional benefits, especially when tailored to the specific needs of this population. At the same time, there is still a need to continue exploring effective and safe program models. This gap continues to limit the development of accessible and sustainable interventions designed to enhance physical functioning in students with intellectual disabilities. The limited theoretical basis and lack of diverse exercise alternatives for this population remain a challenge for researchers aiming to develop more inclusive and adaptable interventions. Therefore, this study aims to determine the effects of combining jump rope and progressive walking for individuals with intellectual disabilities, by applying the principles of frequency, intensity, time, and type of exercise (FITT).

Material and Methods

Participants

The inclusion criteria in this study included students with low ID levels according to a doctor's diagnosis, no comorbidities, no mobility limitations (injuries), not being regional athletes, and agreeing to be research subjects. The exclusion criteria included students with moderate to high levels of ID, those with comorbidities (such as psychiatric and behavioral, neurological, or physical health), regional athletes, those with mobility limitations, and those who were unable to participate in the study.

The research subjects were teenagers with intellectual disability (ID) in a School for Students with Special Needs (SLB N 1 Bantul). Forty students with ID were selected according to the inclusion criteria. Ten students met the exclusion criteria: 3 students had high-level ID, 4 had psychiatric and behavioral comorbidities, and 3 had neurological comorbidities.

Thirty students who met the inclusion criteria were randomly assigned to the experimental group (n = 15) and the control group (n = 15) at a 1:1 ratio. The randomization process was conducted using a computer to ensure allocation confidentiality.

A research team explained the procedures and actions to be taken during the study to all representatives or parents of the students. The explanation included information about data privacy and security. The consent form was completed in a face-to-face session between the research team and the representatives or parents. The completed forms were reviewed by other team members to ensure the accuracy and completeness of the collected data.

This study was assessed for ethical standards based on the seven ethical principles of the WHO under the number T/93.3/UN34.9/PT.01.04/2025.

Study Design

The present study used a two-group pre-test and post-test quasi-experiment design. It aimed to examine the influence of step rope jumping combined with walking exercise. The experimental group (EG) received exercise interventions three times a week for eight weeks. The control group (CG) received no specific treatment. Both groups underwent pre-test and post-test measurements. The detailed research design can be seen in Figure 1.

The instrument used in this study was a fitness test battery. It consisted of a sit-and-reach test to measure flexibility, 1-minute push-ups to measure chest and arm muscle strength, 1-minute sit-ups to measure abdominal muscle strength, 1-minute back-ups to measure back muscle strength, and a 1600-meter run/walk to measure cardiovascular endurance. The fitness test battery had been tested for feasibility in previous research.

Measurement and Training Protocols. A hall with a flat, non-slippery floor was used for the initial data collection (pre-test) and final data collection (post-test). Measurements were taken using a fitness test battery consisting of five items: sit-and-reach, 1-minute push-ups, 1-minute sit-ups, 1-minute back-ups, and a 1600-meter run/walk. There were five measurement stations. Each station had three research assistants who understood the procedures and were responsible for data collection. Measuring tools such as the sit-and-reach box and stopwatches were calibrated to confirm their accuracy.

The initial measurement (pre-test) began with registration. The research team at the registration station provided participants with assessment forms. These were submitted to the measurement team at each station. Before taking measurements, participants were given time to stretch and warm up. After warming up, they proceeded to the first station for flexibility testing.

At each station, the assigned team explained the measurement procedures. After receiving instructions, participants began testing. The measurement team recorded the results on both the research team's form and the participant's own form. The participant then brought the form to the next station. After completing station 1, a rest period of up to two minutes was given before moving on to the next station. All five test items had to be completed in order.

The data collection team verified that each participant followed the procedure and completed each item correctly. Failure to complete one or more items resulted in invalid data or exclusion of that measurement. After finishing the measurements, participants returned the forms to the registration team and began a cool-down period.

To minimize assessment bias, outcome evaluators were blinded to group allocation during both the pre-test and post-test. Evaluators at each testing station were not informed of participants' group assignments.

After completing the measurements, experimental group were given an intervention consisting of a combination of step rope jumping and walking (step rope jump for 1 minute followed by walking for 1.5 minutes, repeated for 20-30 minutes) with an intensity of 70%-85% of maximum heart rate. Students performed static and dynamic warm-ups before and after the intervention was given. Intervention performed three times a week for eight weeks. The control group must complete 24 training sessions, with the tolerance of replacing training sessions with research assistants if they are unable to attend according to the schedule. A total of 10 research assistants and 3 teachers accompanied each training session to monitor training adherence to the established protocol. Two health care workers and one therapist were also present at each training session and measurement session to be prepared for any emergencies that might occur. After the intervention was completed, a final measurement (post-test) was conducted. The procedure and location for the post-test were the same as for the initial measurement (pre-test). Specifically, the pre-test and post-test were conducted outside the intervention period. Measurement and training protocols can be clearly seen in Figure 1. No participants dropped out during the intervention period. All 30 students completed both pre- and post-test assessments. As such, no imputation or data replacement was required for missing values.

Statistical analysis

Data analysis techniques were performed using ANCOVA. ANCOVA was used to compare differences between groups while considering other factors, specifically the baseline measurement results. The significance level was set at 0.05. The partial eta-squared (η^2_p) value was reported to indicate the proportion of explained variance. A post hoc test (pholm) was conducted to determine differences between groups. Assumption testing, in the form of a normality test, homogeneity test, and linearity test, was a prerequisite before conducting ANCOVA. Data analysis was performed using the JASP application.

Results

Table 1 presents the sample characteristics, including age, gender, ID level, training background, and comorbidities.

Table 2 presents descriptive statistics for five measurements based on the mean and standard deviation of baseline and post-test results for each group. The post-test mean increased in both the experimental and control groups. However, the increase was greater in the experimental group. The complete differences are presented in Table 2.

Table 3 presents the results of the assumption checks for the ANCOVA test, which include three components: the normality test (Shapiro-Wilk), the homogeneity test (Levene's), and the linearity test (linear regression). The p-values in the Shapiro-Wilk test were greater than 0.05, indicating that the data were normally distributed. The Levene's test p-values were also greater than 0.05, indicating homogeneity of variance.

In the linear regression test, the correlation coefficient (R) was greater than 0.8 or close to 1, indicating a strong relationship. The p-values in this test were below 0.05, showing a statistically significant relationship between the dependent and independent variables. These results confirm that the assumptions of normality, homogeneity, and linearity were met, validating the use of ANCOVA.

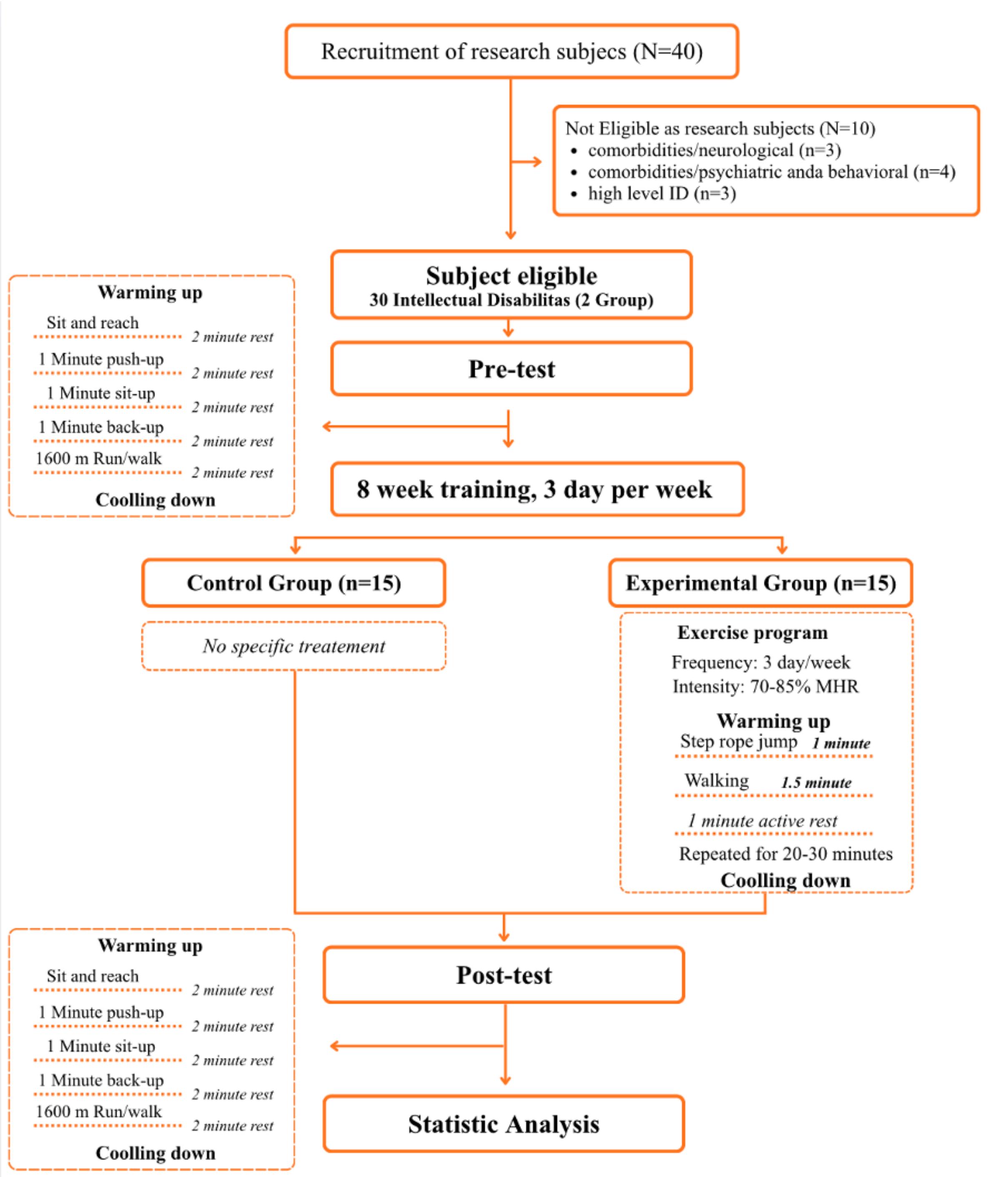

Figure 1. Experimental design

Table 1. Sample Characteristics

Characteristic	Total Sample (n = 30)	CG (n = 15)	EG (n = 15)
Age M (SD)	16.53 (1.93)	16.67 (1.74)	16.40 (2.09)
Gender, n (%)			
Male	22 (73%)	11 (73%)	11 (73%)
Female	8 (27%)	4 (27%)	4 (27%)
ID Level, n (%)			
High	0 (0%)	0 (0%)	0 (0%)
Moderate	0 (0%)	0 (0%)	0 (0%)

Table 1. (Continued)

Characteristic	Total Sample (n = 30)	CG (n = 15)	EG (n = 15)
Low	30 (100%)	15 (100%)	15 (100%)
Training Background, n (%)			
Occasional (0–1 h/week)	17 (57%)	8 (53%)	9 (60%)
Regular (1–3 h/week)	13 (43%)	7 (47%)	6 (40%)
Intense (>3 h/week)	0 (0%)	0 (0%)	0 (0%)
Comorbidities, n (%)			
Psychiatric and behavioral	0 (0%)	0 (0%)	0 (0%)
Neurological	0 (0%)	0 (0%)	0 (0%)
Physical health	0 (0%)	0 (0%)	0 (0%)

Note. EG = Experimental Group; CG = Control Group; n = number of participants.

Table 2. Descriptive Statistics

Physical Fitness Indicator	Group	Baseline Mean	SD	Post-test Mean	SD
Flexibility (cm)	CG	10.80	5.63	12.47	5.26
	EG	13.27	6.47	16.27	7.19
Arm strength (rep/min)	CG	15.53	5.38	15.87	5.45
	EG	16.67	4.05	19.73	4.25
Abdominal strength (rep/min)	CG	14.40	7.07	15.93	6.93
	EG	14.67	4.78	18.53	4.78
Back strength (rep/min)	CG	22.47	7.48	25.07	7.03
	EG	22.53	7.57	31.53	5.84
Cardiovascular endurance (min)	CG	16.45	3.76	15.25	3.74
	EG	14.72	3.00	12.07	2.89

Note. EG = Experimental Group; CG = Control Group; SD = Standard Deviation. lexibility (cm): higher values indicate better results. Strength (repetitions/minute): higher repetitions indicate better results. Cardiovascular endurance (minutes): lower values indicate better results.

Table 3. Assumption Check Results

Physical Fitness Indicator	Shapiro-Wilk p (EG)	Shapiro-Wilk p (CG)	Levene's p	R	Linear Regression p
Flexibility (cm)	0.45	0.16	0.47	0.99	< 0.001
Arm strength (rep/min)	0.26	0.37	0.90	0.91	< 0.001
Abdominal strength (rep/min)	0.33	0.41	0.52	0.97	< 0.001
Back strength (rep/min)	0.44	0.72	0.06	0.81	< 0.001
Cardiovascular endurance (min)	0.21	0.52	0.09	0.98	< 0.001

Note. EG = Experimental Group; CG = Control Group; R = Multiple Correlation Coefficient; p = significance level. For Shapiro-Wilk and Levene's tests, p > 0.05 indicates assumption met. For linear regression, p < 0.05 indicates significance.

Table 4. ANCOVA Analysis Results

Physical Fitness Indicator	N	F (1, 27)	p-value	η^2_p	95% CI for η^2_p	pholm
Flexibility (cm)	15	11.47	< 0.001	0.34	0.08 – 0.56	< 0.001
Arm strength (rep/min)	15	15.25	< 0.001	0.36	0.09 – 0.58	< 0.001
Abdominal strength (rep/min)	15	19.95	< 0.001	0.43	0.15 – 0.63	< 0.001
Back strength (rep/min)	15	16.65	< 0.001	0.38	0.11 – 0.59	< 0.001
Cardiovascular endurance (min)	15	29.49	< 0.001	0.52	0.25 – 0.69	< 0.001

Note. F(1, 27) = ANCOVA test statistic controlling for pre-test scores. p = significance level (p < 0.05); η^2p = partial eta-squared: 0.01 = small effect, 0.06 = moderate effect, 0.14 = large effect; pholm = Holm-adjusted post hoc test (significant if pholm < 0.01); CI = Confidence Interval.

ANCOVA was performed with the baseline score as a covariate. Partial eta-squared (η^2_p) values were reported to indicate the proportion of variance explained. Post hoc tests were conducted to determine differences between groups (Table 4). The p-values for flexibility, arm and chest strength, abdominal strength, back strength, and cardiovascular endurance were all below 0.01. This indicates a significant effect between the experimental group (step rope and walking intervention) and the control group, after adjusting for baseline differences.

An η^2_p value greater than 0.14 indicates a large effect size. The post hoc test results using the Holm adjustment showed pholm < 0.001, indicating significant differences between the groups.

Discussion

Theoretically, physical fitness is influenced by age, gender, and training. Programmed exercise is a common method used by practitioners to improve fitness. This study aimed to determine the effects of combining jump rope and progressive walking for individuals with intellectual disabilities by applying the principles of frequency, intensity, time, and type of exercise (FITT). The results of the present study showed improvements in physical fitness among children with intellectual disabilities after eight weeks of the jump rope and walking intervention. These changes were evident in flexibility, cardiovascular endurance, muscular strength, and muscular endurance. Exercise is an activity that requires planned, structured, and repetitive physical effort to maintain or improve health and fitness [24, 25]. The combination of jumping rope and walking given to individuals with disabilities was a planned exercise that followed key elements of a training program. To improve physical fitness, the exercise dose must be tailored to individual needs and based on four components: frequency, intensity, time, and type of exercise (FITT) [26]. FITT is a framework used in physical conditioning programs that affects cardiorespiratory endurance, muscular strength and endurance, and flexibility [27]. The results of this study, which showed improvements in each physical fitness indicator, support the effectiveness of the structured exercise program applied.

These experimental results align with other studies showing that progressive rope jumping exercises improve physical fitness and cardiovascular health, as well as increase exercise tolerance in adolescent students with moderate intellectual disabilities [28]. In addition, skipping and walking provided benefits not only for individuals with intellectual disabilities but also for non-disabled individuals by improving their physical fitness [29]. Skipping was also applied to physical education students and was found to increase cardiovascular efficiency and lower leg muscle strength [30]. Step rope jumping is a simple and economical exercise believed to improve cardiovascular capacity. It is also considered an alternative form of training for individuals with limited time for physical activity [29]. Step rope jumping exercises also provide benefits for individuals with obesity and may reduce the risk of cardiovascular disease [31]. Another study found that step rope jumping had a greater impact on motor components of fitness, especially lower leg muscle explosive power [32]. Although step rope jumping showed short-term benefits for cardiovascular fitness, other training methods, such as jogging, were found to be more effective in improving cardiovascular capacity [33].

Besides step rope jumping and jogging, walking can also strengthen muscles, improve body flexibility, and increase motivation in individuals with intellectual disabilities to engage in physical activity [1]. An intervention combining walking with multicomponent communication was shown to be effective in increasing physical activity among people with disabilities [2]. Various forms of intervention such as jumping rope, jogging, and walking, implemented with different durations and training methods, have been reported to produce benefits for physical fitness. The differences in effects observed between exercise programs are influenced by movement style, muscle focus, and the nature of the activity. In this study, the intervention combined jumping rope and walking, using the FITT principle as the basis for program design. This approach has not been widely applied in previous studies involving individuals with intellectual disabilities. The results clearly show positive effects on each physical fitness indicator.

An increase in physical activity has a positive impact on the well-being of individuals with intellectual disabilities [6]. This finding is consistent with the present study, which showed that combining step rope jumping and walking had a positive impact on flexibility and muscle strength. Training interventions that combine multiple exercise models are believed to be more effective in improving functional capacity, cardiorespiratory fitness, and muscular strength in individuals with intellectual disabilities [34]. Policymakers should integrate walking programs into health promotion strategies and provide training for professionals or caregivers to ensure that such programs are implemented safely for individuals with intellectual disabilities [35]. Caregivers and professionals need to understand the fundamentals of exercise, given its benefits for this population. Exercise is an effective way for anyone to maintain fitness and health. However, individuals with intellectual disabilities are generally less active compared to those without disabilities [36]. Psychological, environmental, and resource-related barriers often prevent participation in physical activity among people with disabilities. This lack of participation raises health concerns in the disabled population. As a result, practitioners and academics continue to develop safe and adaptable exercise options for this community.

The development of economical equipment, tailored training methods, and evaluations to monitor training progress has supported individuals with disabilities in maintaining their health [37]. In the present study, the authors developed a step rope jumping exercise combined with walking to provide an alternative physical activity for individuals with intellectual disabilities. Although the findings indicated positive effects on physical fitness, further testing involving a larger and more diverse sample is needed. In addition to evaluating the benefits of step rope jumping and walking, future studies should explore other types of exercises to increase the variety of accessible training options for this population. This is particularly important because individuals with intellectual disabilities are vulnerable to both physical and mental health problems and require accessible, holistic therapies [12].

The application of a training model that combines jump rope and walking, based on the FITT principle and adapted to individuals with intellectual disabilities, has both pedagogical and clinical implications.

First, jump rope and walking exercises following the FITT framework can be considered by stakeholders when designing interventions for students with ID.

Second, structured exercise programs support the development of motor skills.

Third, such programs help students learn basic concepts and rules.

Fourth, group-based interventions may improve social interaction skills.

Fifth, designing programs according to the specific characteristics of students with ID contributes to creating an inclusive learning and training environment.

Limitations of the Study

Although this study was designed in accordance with research standards, several limitations were beyond the researchers' control.

First, the small sample size and the inclusion of only participants with low levels of intellectual disability may limit the generalizability of the findings.

Second, participants may have experienced acute physical or psychological responses to the intervention, potentially influencing the results.

Third, external factors such as changes in weather conditions during the intervention period could have affected performance.

Fourth, limitations in available measurement equipment restricted the ability to conduct laboratory-based physiological assessments, and there was a possibility of recording errors during data collection.

Conclusions

An eight-week combined jump rope and walking exercise program for individuals with intellectual disabilities resulted in improvements in body flexibility, arm and chest muscle strength, abdominal and back muscle strength, and cardiovascular endurance, based on comparisons with baseline measurements. These baseline measurements indicated that both the control and experimental groups had relatively similar initial physical fitness levels.

Therefore, it can be concluded that the intervention effectively improved the physical fitness of the experimental group. The findings of this study contribute to the growing body of knowledge on exercise interventions suitable for individuals with intellectual disabilities. As such interventions require careful design and adaptation, future research should continue to explore different types of exercise, supported by theory, to develop appropriate strategies for maintaining health and fitness in this population. Supporting physical fitness is essential for improving their overall quality of life.

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Conflict of Interest

The authors declare no potential conflicts of interest.

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ORIGINAL ARTICLE

Changes in the static balance of primary school students after six months of wrestling training

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

Abstract

Background and Study Aim Balance plays a key role in many sports, particularly those that require precise movements and continuous body control. The aim of the study was to verify or disprove changes in the ability to maintain static balance after six months of wrestling training under conditions of reduced visual input and limited support surface.

Material and Methods The study included twenty-three male primary school pupils who participated in wrestling training. Their average age was 13.00 ± 1.48 years. The average height was 156.7 ± 35.22 cm, and the average body weight was 58.7 ± 19.00 kg. Training experience ranged from 1 to 2 years. The Romberg test was conducted using a freeSTEP STANDARD stabilometric platform with a sampling frequency of 250–400 Hz to assess static balance. The analysed stabilometric parameters included: total path length (PL) of foot pressure; confidence ellipse area (CEA); mean velocity (MV), defined as the total CoP path in 30 seconds; root mean square (RMS) of sway in the medial-lateral direction (X-RMS); and RMS in the anteroposterior direction (Y-RMS).

Results For the two-leg standing test, the values of PL, CEA, MV, X-RMS, and Y-RMS showed no statistically significant differences ($p > 0.05$). The effect sizes were small ($\eta^2 < 0.10$), indicating low sensitivity of these parameters to the intervention. In the one-leg standing test, on both the right and left legs, no significant differences were found ($p > 0.05$) in PL, CEA, X-RMS, and Y-RMS between eyes-open (EO) and eyes-closed (EC) conditions. However, mean sway velocity (MV) increased significantly under EC conditions compared to EO, with a significance level of $p < 0.05$.

Conclusions The lack of significant differences in the two-leg stance may reflect stable postural control development in this age group. However, selective neuromuscular adaptation in postural control was observed under more demanding one-leg stance conditions. Therefore, it is advisable to modify wrestling training programmes for schoolchildren to include more complex equilibrium and sensorimotor challenges

Keywords: body balance, stabilometria, wrestlers, stabilometric mat

Introduction

Maintaining proper balance is one of the key motor skills in children and adolescents. Its development results from the complex cooperation of multiple body systems. In adolescents over the age of eleven, the ability to maintain a stable posture depends primarily on the coordinated integration of three main sensory systems: visual, vestibular, and proprioceptive.

The visual system provides information about the position of the body in relation to its surroundings. The vestibular organ in the inner ear registers linear and angular accelerations of the head, allowing for rapid detection of changes in movement trajectory [1]. Proprioception enables internal awareness of body position and locomotion control through signals from muscle, tendon, and joint receptors. Integration of these sensory inputs in the central nervous system allows accurate assessment of postural stability and the selection of appropriate corrective strategies [2]. In adolescents, whose nervous systems are still developing through myelination and synaptic formation, the effectiveness of this integration may vary depending on fatigue, visual input, or environmental conditions. Research also indicates gender differences in segmental stabilisation strategies. Girls aged 14–15 years tend to display more effective stabilization mechanisms than boys [3].

The second factor influencing balance is the ability of the muscular system to generate force and maintain tension over time. The deep muscles of the torso, including the transverse abdominis, multifidus, and diaphragm, form a so-called "muscular corset" that stabilizes the spine and pelvis during changes in position. Equally important is the strength and endurance of the lower limb muscles, which control movement in the foot, knee, and hip joints. In children over the age of 11, whose muscle tissue is still adapting to bone growth and changes in body weight, strength training can significantly improve the ability to maintain stable posture

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during tasks that require both weight bearing and dynamic movement [4, 5].

The third factor affecting balance is the flexibility of muscle and tendon tissues, as well as the range of motion in the joints. High flexibility in the posterior chain, calf, and hip-lumbar muscles allows for cushioning shifts in the centre of gravity and smooth adjustment of the support point. In contrast, limited mobility in the hip, knee, or ankle joints can lead to suboptimal movement patterns and impaired postural control. Regular stretching exercises, combined with joint mobilisation techniques, support full range of motion and improve the ability of young athletes to respond precisely to changes in body position [6, 7].

In sports practice and wrestling training, maintaining a wide, stable base of support is essential when performing holds and takedown attempts. This involves consciously positioning the feet and knees at the correct angle to distribute body weight evenly across the ground surface [8]. This positioning helps the competitor minimize force vectors that could cause a loss of balance. These forces may come from their own momentum during the initiation of a technique or from the opponent's defensive actions. A stable base also enables the generation of maximum force without the risk of losing contact with the mat. In techniques that involve transferring the opponent's weight, such as a hip throw, this translates into more fluid and powerful movements. Balance and muscle strength are therefore key factors influencing the ability to perform wrestling techniques [6, 9].

Preventing loss of balance due to external forces, such as pulling on the leg or jerking the belt, requires many hours of practicing automatic postural correction mechanisms. In wrestling training, static balance is developed not only through standard tests or isometric positions but also through resistance simulations using rubber bands, a partner, or special handles. The goal is to develop the athlete's ability to detect shifts in their centre of gravity and produce an appropriate response. This includes both antagonistic reactions, such as crossing the knees, and synergistic ones, such as contraction of the quadriceps or thigh adductors. These responses are essential for maintaining an advantageous position [10, 11, 12].

Dynamic balance plays a key role in a wrestler's combat manoeuvres. This is due to the precise transfer of the centre of gravity during changes in movement level and direction. Shifting the trajectory of movement, such as moving from an upright position to a deep forward bend, causes the centre of mass (CoM) to move forward and downward. This reduces the static margin of stability. To maintain balance, the body must coordinate eccentric muscle activity, which controls the descent, and isometric muscle activity, which maintains position in the new plane. It must also activate signals from the vestibular system and joint proprioceptors to anticipate and compensate for dynamic forces while maintaining contact with the mat. Simultaneously, the central nervous system must quickly shift the base of support to the expected contact point between the feet and the mat. This requires precise correction of the centre of pressure (CoP) trajectory and modulation of muscle-tendon tension [13].

Between the ages of 11 and 15, the nervous system develops at a highly dynamic rate. Synaptic expansion and selection occur first, improving sensorimotor responses. This is followed by increased myelination, which speeds up nerve impulse conduction and enhances the precision of motor coordination. As a result, children in this age group gradually improve their ability to stabilize the centre of gravity in response to mechanical stimuli. This makes the period particularly suitable for training focused on postural control, including in sports such as wrestling.

The aim of this study was to examine changes in the balance abilities of primary school students after six months of wrestling training.

Material and Methods

Participants

All participants were recruited voluntarily and were informed about the nature of the experiment. The purpose of the research and possible risks were clearly explained. Participants could withdraw from the study at any time. Written consent was obtained from the participants' legal guardians before the study began. The study was conducted in accordance with the guidelines of the Helsinki Declaration and was approved by the Research Ethics Committee. The initial study included a group of 33 students. However, only 23 students took part in the second assessment. Only the results of those who participated in both studies were included in the final analysis.

Research Design

The tests were conducted in two periods. The first test took place in October 2024, after the start of the school year and a two-month summer break. The second test was carried out six months later, in April 2025. All tests were conducted before the start of wrestling training sessions.

The testing took place in the same room, under constant environmental conditions. These included uniform lighting, no noise or unnecessary external stimuli, and a stable temperature. To ensure repeatability, the tests were performed individually, in the presence of the examiner. The total duration of the procedure for one person was approximately 2 minutes. This included 1 minute of preparation and two 30-second measurements.

Each subject was measured barefoot, standing in the centre of the platform in a relaxed position. The feet were placed parallel at hip width, and the arms remained lowered alongside the torso. Participants were instructed to stand as still as possible and maintain a stable posture throughout the test.

Wrestling training sessions for young people aged 11–14 were held three times per week, each lasting 90 minutes. The structure of the classes followed the early stage of targeted training. It included the development of basic motor skills, techniques, and elements of task-oriented combat. Each session had four fixed parts: warm-up (15–20 minutes), main technical and motor part (55–60 minutes), task-oriented combat (10–15 minutes), and a cool-down phase (5 minutes). The warm-up prepared the body for exercise, activated the neuromuscular system, and developed basic motor coordination. The technical programme covered the fundamentals of wrestling, adjusted to the participants' level of development. Teaching was conducted in pairs, progressing from static to dynamic, then to semi-task forms. Motor tasks were selected to support the development of functional strength, balance, agility, and adaptability to changes in balance. The training volume was distributed as follows: 40% technique, 35% motor skills, 15% task-based combat, and 10% warm-up and cool-down.

The Romberg test using the freeSTEP STANDARD stabilometric platform (FreeMED BASE, Poland) was used to assess balance ability. The study was planned and conducted in accordance with applicable ethical standards.

Test of balance ability

Postural stabilography was used to assess balance ability [14]. Posturography tests are classified as objective methods for evaluating balance. They are based on measuring the displacement of the point of application of the resultant ground reaction forces. The measurement of body sway indices is used to assess the function of the postural control system and to detect imbalances and risk of falls. Postural stability was measured in static conditions, on a stationary surface, using a FreeMED BASE stabilometric mat (Italy) with FreeSTEP 2.0 software. The device enables analysis of the distribution of foot pressure on the ground, with a sampling frequency of 250 Hz in real time. Two measurements were taken using the standard Romberg test procedure. The first was a 30-second test standing barefoot with eyes open. The second was a 30-second test standing barefoot with eyes closed. During the procedure, subjects were belayed to prevent falls. Measurements were taken before the start of an international wrestling tournament (Figure 1).

Figure 1. Performing the Romberg test, standing on both legs (AI-generated example image)

The analysed stabilometric parameters used to measure the range of centre of pressure (CoP) deviation were as follows: total path length (PL) of foot pressure on the ground; confidence ellipse area (CEA), defined as the smallest ellipse that covers 95% of the CoP points; mean velocity (MV), defined as the total distance travelled by the CoP in 30 seconds; root mean square (RMS) amplitude of sway in the medial-lateral direction (X-RMS); and RMS amplitude of sway in the anteroposterior direction (Y-RMS).

Statistical analysis

The Shapiro–Wilk W-test ($\alpha = 0.05$) was used to assess the normality of distributions. The results showed that the values obtained for the CoP displacement range did not follow a normal distribution, so the data were logarithmised. The Mann–Whitney U test does not require normality or homogeneity of variance. It is suitable for quantitative variables that do not meet the assumptions of parametric tests, which corresponds to the nature of stabilometric parameters. The Mann–Whitney U test (Wilcoxon rank-sum) for repeated measures was used to assess the significance of differences between eyes-open and eyes-closed conditions. Detailed post-hoc comparisons between pairs of means were performed using the Tukey test.

η^2 is a measure of effect size used in both parametric (e.g. ANOVA) and non-parametric comparisons. Since this study involved comparing two sets of results (e.g. eyes open vs. eyes closed), η^2 was used to quantify the influence of the condition on the analysed stabilometric parameters. The thresholds for effect size were: $\eta^2 > 0.01$ for a small effect, $\eta^2 < 0.06$ to < 0.14 for a medium effect, and $\eta^2 \geqslant 0.14$ for a large effect.

Cohen's f^2 was also used to assess effect size independently of sample size. This allowed interpretation of the practical significance of the results. Cohen's f^2 was classified as small ($f^2 \approx 0.02$), medium ($f^2 \approx 0.15$), or large ($f^2 \approx 0.35$).

All analyses were conducted using STATISTICA, TIBCO Software Inc. (2017), version 13. A significance level of $p < 0.05$ was used.

Results

In children who practise wrestling, the ability to maintain static balance remains at a comparable level regardless of the variables analysed. The lack of significant differences may indicate stable development of postural control mechanisms in this age group. Regular sports training, including wrestling, supports the development of proprioception and balance. However, at a certain level of advancement, individual differences may become less apparent. The values of the PL, CEA, MV, X-RMS, and Y-RMS parameters did not differ significantly ($p > 0.05$) (Table 1).

The results of statistical analysis for the one-leg

Table 1. Results, p-values, and effect sizes of the tested athletes before and after 6 months of training while standing on both feet (EO and EC).

Stabilometric variables	Before	After	Effect size f^2	p-value
		PL (mm)		
EO	118.08 ±154.91	283.11 ±439.84	0.098	0.486
EC	168.95 ±168.90	127.39 ±140.19	0.056	0.687
Effect size η^2	0.021	0.091		
p-value	0.880	0.050		
		CEA (mm^2)		
EO	243.39 ±118.85	247.85 ±130.30	0.011	0.942
EC	262.74 ±.131.85	232.14 ±89.30	0.011	0.942
Effect size η^2	0.058	0.066		
p-value	0.674	0.634		
		MV (mm/s)		
EO	8.51 ±4.13	8.55 ±4.39	0.013	0.925
EC	8.95 ±4.48	7.87 ±3.13	0.069	0.621
Effect size η^2	0.009	0.052		
p-value	0.949	0.721		
		X-RMS (mm)		
EO	0.34 ±0.16	4.36 ±1.47	0.005	0.969
EC	0.42 ±0.24	0.32 ±0.12	0.107	0.440
Effect size η^2	0.043	0.042		
p-value	0.754	0.762		
		Y-RMS (mm)		
EO	0.23 ±0.09	0.31 ±0.27	0.053	0.705
EC	0.31 ±0.17	0.29 ±0.10	0.042	0.762
Effect size η^2	0.098	0.001		
p-value	0.481	0.996		

NOTE: EO – eyes open; EC – eyes closed; PL – total path length; CEA – confidence ellipse area; MV – mean velocity; X-RMS – root mean square of sway in the medial-lateral direction; Y-RMS – root mean square of sway in the anteroposterior direction.

standing test, both on the right and left leg, showed no statistically significant differences ($p > 0.05$) in PL, CEA, X-RMS, and Y-RMS between the EO and EC conditions. This indicates that the ability to maintain balance in a one-leg standing position was similar regardless of visual control. At the same time, mean velocity of sway (MV) increased significantly under visual restriction (EC) compared to eyes-open conditions (EO), with a significance level of $p < 0.05$. This increase suggests greater neuromuscular activity required to compensate for the loss of visual input and to maintain postural stability (Tables 2, 3).

Table 2. Results, p-values, and effect sizes of the tested athletes before and after 6 months of training while standing on the right leg (EO and EC).

Stabilometric variables	Before	After	Effect size f^2	p-value
		PL (mm)		
EO	432.52 ±228.89	390.14 ±229,23	0.032	0.839
EC	24782.75 ±41944.76	9506.83 ±26938.64	0.093	0.504
Effect size η^2	0.183	0.290		
p-value	0.215	0.041		
		CEA (mm^2)		
EO	372.57 ±236.29	321.14 ±246.23	0.115	0.474
EC	1072.47 ±396.08	787.68 ±249.97	0.056	0.687
Effect size η^2	0.231	0.224		
p-value	0.109	0.109		
		MV (mm/s)		
EO	26.55 ±26.24	21.59 ±11.83	0.077	0.626
EC	95.19 ±37.28	64.63 ±21.16	0.242	0.080
Effect size η^2	0.543	0.387		
p-value	0.001	0.006		
		X-RMS (mm)		
EO	7.44 ±6.97	6.15 ±5.75	0.097	0.545
EC	11.77 ±8.51	9.13 ±5.39	0.088	0.534
Effect size η^2	0.134	0.201		
p-value	0.342	0.152		
		Y-RMS (mm)		
EO	3.98 ±4.50	2.76 ±3.13	0.063	0.696
EC	8.64 ±5.21	4.34 ±2.71	0.104	0.453
Effect size η^2	0.147	0.255		
p-value	0.288	0.069		

NOTE: EO – eyes open; EC – eyes closed; PL – total path length; CEA – confidence ellipse area; MV – mean velocity; X-RMS – root mean square of sway in the medial-lateral direction; Y-RMS – root mean square of sway in the anteroposterior direction.

Table 3. Results, p-values, and effect sizes of the tested athletes before and after 6 months of training while standing on the left leg (EO and EC).

Stabilometric variables	Before	After	Effect size f^2	p-value
		PL (mm)		
EO	550.54 ±576,42	367.94 ±186.32	0.031	0.826
EC	2779.34 ±1427.59	3066.41 ±1222.86	0.037	0.795
Effect size η^2	0.207	0.232		
p-value	0.136	0.097		
		CEA (mm^2)		
EO	360.68 ±99.27	361.71 ±114.43	0.055	0.698
EC	738.73 ±239.63	766.76 ±203.95	0.104	0.453
Effect size η^2	0.110	0.277		
p-value	0.434	0.048		
		MV (mm/s)		
EO	24.88 ±7.24	25.63 ±8.36	0.098	0.481
EC	65.30 ±23.49	63.61 ±16.69	0.029	0.833
Effect size η^2	0.428	0.378		
p-value	0.002	0.006		
		X-RMS (mm)		
EO	7.13 ±4.61	6.66 ±4.18	0.056	0.687
EC	6.17 ±4.54	8.19 ±3.43	0.077	0.576
Effect size η^2	0.039	0.117		
p-value	0.776	0.399		
		Y-RMS (mm)		
EO	1.64 ±0.65	1.59 ±0.85	0.072	0.605
EC	4.84 ±2.82	3.59 ±1.79	0.118	0.393
Effect size η^2	0.233	0.067		
p-value	0.093	0.627		

NOTE: EO – eyes open; EC – eyes closed; PL – total path length; CEA – confidence ellipse area; MV – mean velocity; X-RMS – root mean square of sway in the medial-lateral direction; Y-RMS – root mean square of sway in the anteroposterior direction.

Discussion

The aim of this study was to evaluate changes in the ability to maintain static balance among school-aged boys after six months of wrestling training. The analysis focused on stabilometric parameters under different visual and support conditions. The results showed no statistically significant changes in the parameters of postural sway (PL, CEA, MV, X-RMS, Y-RMS) during the two-leg standing test. This suggests that basic postural control mechanisms remained stable over the training period. Similarly, no significant differences were observed in most parameters during the one-leg standing test, regardless of whether the eyes were open or closed. However, a significant increase in mean velocity (MV) under eyes-closed conditions was found, indicating an elevated neuromuscular response required to maintain balance without visual input.

Muehlbauer et al. found an increase in postural sway when the base of support was reduced, such as moving from a two-legged stance in step and tandem positions to a one-legged stance. Changes in sensory input also affected sway, progressing from standing with eyes open on a hard surface, to eyes open on a foam surface, and finally to eyes closed on a hard surface [15].

In our study, during the two-leg standing test with EO and EC, no statistically significant changes were observed in the length of the centre of pressure (PL) trajectory, the range of maximum deflections, or the confidence ellipse area (CEA). This lack of improvement in basic static stability parameters suggests that in children aged 11–15, the mechanisms for maintaining balance under full visual conditions were already relatively well developed before the intervention.

In young, healthy, and physically active individuals, it is often observed that under standard test conditions (full visual input, stable surface), the adaptive reserve of the postural system is small or difficult to detect. The literature on balance training in young people emphasizes that greater effects are seen when high-difficulty stimuli are used (e.g. altered support conditions, sensory changes) rather than during simple static tasks [16].

Although the research group had limited training experience (1–2 years), it can be assumed that the participants had already achieved a high level of stability under 'easy' conditions. This may explain why the intervention did not result in significant further improvements in the same parameters.

Studies by other authors indicate that none of the training modalities examined had a measurable effect on balance performance in adolescents. However, the results of one-dimensional analyses should be interpreted with caution, as training modalities were treated as single factors, without accounting for potential interactions between them [17, 18].

In addition, physical fitness and physical activity may play an important role, as they help mitigate the negative effects of excess body fat on postural control in children [19]. Training in direct combat sports, even in milder forms, is particularly valuable as part of a comprehensive approach to youth physical development [20, 21].

Although average values did not change significantly, individual differences (e.g. between more and less 'talented' participants) may be substantial. This increases variance and reduces the ability to detect effects (statistical power). Standard static posturography may also lack the sensitivity to detect subtle adaptations in well-trained groups.

A noticeable, though statistically insignificant, tendency toward increased deviations in the front–back axis may indicate a subtle shift in corrective strategies. Participants more frequently made small movement adjustments (micro-corrections) to stabilize their centre of gravity. This may be an early sign of sensorimotor adaptation that is not captured by standard parameters such as PL or CEA, but may suggest the direction of adaptive changes in more demanding tasks.

Although trends such as shorter trajectories and reduced sway areas were observed, their statistical insignificance ($p > 0.05$) suggests that interventions based mainly on static or moderate tasks may not provide sufficient stimulation for balance control systems under conditions of visual deprivation. In sports like wrestling, where athletes must react dynamically to the opponent's movements and sudden shifts in the centre of gravity, static training is likely insufficient.

The results of our study are consistent with the findings of Muehlbauer et al. [15], who demonstrated a significant increase in postural sway with a reduced base of support and altered sensory input. Their effects were clear ($p < 0.01$; $\eta^2 > 0.30$), indicating that difficult conditions, such as standing on one leg or tandem positions with limited visual information, strongly engage the postural system.

In our study, the lack of significant changes in bipedal standing with EO and EC (all $p > 0.05$; small effects: $\eta^2 < 0.10$, $d < 0.20$) confirms that the tasks used were likely not demanding enough to trigger measurable adaptations.

It is important to note that static stability parameters, such as COP trajectory length (PL) and confidence ellipse area (CEA), are relatively resistant to change in young, healthy, and physically active individuals. This has also been confirmed by earlier studies on adolescents [16]. In the 11–15 age group, especially among those with some sports experience, the postural system functions effectively even before training. This is evident in our study, where participants showed stable baseline parameters. Training effects in easy conditions are therefore difficult to detect and usually only appear in tasks with greater sensorimotor complexity.

Given their short training history (1 to 2 years), it can be assumed that the participants are still developing their motor skills. However, their level of static stability is already relatively high. This is consistent with the findings of Gebel et al. [17] and more recent analyses by Muehlbauer and Schedler [18]. These studies indicate that training modalities in adolescence do not always lead to significant improvements in classic balance tests. In addition, analysing only single-factor effects may overlook potential interactions between types of stimuli.

It is also important to consider the role of physiological factors. Physical activity and general fitness can partially compensate for the negative impact of excess body fat on postural stability [19]. Therefore, training activities for children, especially during periods of rapid physical development, should be varied. They should also include forms of combat adapted to the age and abilities of the participants, as confirmed by studies on mild forms of combat sports [20, 21].

Although statistically insignificant trends were observed in our measurements, such as a slight shortening of the COP trajectory and a reduction in CEA, these effects were small ($\eta^2 < 0.06$) and did not reach significance. This may result from the limited sensitivity of classical posturography and from considerable individual differences between athletes. These differences increase variance and reduce statistical power. They are particularly noticeable in populations of young athletes.

A subtle but insignificant tendency toward increased deviations in the anterior–posterior (AP) axis was also observed. This may suggest a shift in stabilization strategy, with participants using micro-movement corrections more frequently. Although this effect was small ($d < 0.30$), it may represent an early sign of sensorimotor adaptation. Such changes may become more visible in more demanding tasks.

In summary, the absence of statistically significant changes ($p > 0.05$) in the presence of small effects ($\eta^2 < 0.10$) suggests that training based mainly on static or moderately difficult tasks is not a sufficient stimulus to improve balance under conditions of visual deprivation. In sports such as wrestling, where quick reactions to an opponent›s movements and dynamic shifts in the centre of gravity are essential, static tasks are not enough. Exposure to dynamic, unpredictable, and multitask conditions may be more effective.

Therefore, attention is drawn to the method and results of body balance disturbance tolerance skills (BBDTS) using the Rotational Test (RT) [22]. This test alternates between two phenomena referred to in operational terms as dynamic balance and static balance. A four-point quantitative and qualitative scale is used for each of the six landings on a fixed line after alternating jumps with a 360° rotation to the right and left. The score ranges from 0, for both feet landing on the line again, to 3, for conventional penalty points in the case of hand support or a fall. This scoring system provides sufficient differentiation between participants.

The brief moment of posture correction while standing symmetrically on a fixed line, before performing the next rotational jump, represents the static balance component. This is part of the six-task RT set and can be interpreted as a motor simulation of situations in which a wrestler attacks or counterattacks by rotating their body after compensating for a loss of balance caused by the opponent.

The results of several studies using RT show that the main differentiating factors are an individual's innate or trained abilities, external circumstances (such as darkness or location of rescue operations) [23, 24, 25, 26], or internal circumstances (such as physical exertion) before performing RT [27, 28, 29, 30].

Combining the results from both tools, the posturography test and RT, may provide new insights and practical applications in combat sports, self-defence, or rescue training. This approach is also consistent with the concept of complementary somatic health diagnosis [31, 32].

Limitations of the study

Due to possible high individual variability, training should be tailored to the individual. For example, reactions such as changes in sway speed or deviations can be monitored, and difficulty levels adjusted based on the results. It is therefore advisable to consider longer intervention periods or more frequent sessions to allow for advanced adaptations, particularly under visual deprivation conditions.

Conclusions

As a result of wrestling training in schoolchildren aged 11 to 15 over a period of six months, no statistically significant changes were found in static balance ability. In groups with relatively well-developed balance, such as children who practise wrestling, standard static tasks performed on a stable surface with eyes open may not lead to further improvement in bipedal postural control.

It is advisable to modify the sports training programme for schoolchildren who practise wrestling by increasing the complexity of balance and sensorimotor challenges. Current static training, performed on a stable surface with full visual control, may be insufficient for further development of postural control.

However, signs of selective neuromuscular adaptation were observed in more demanding one-leg standing tasks. Therefore, it is recommended to introduce more difficult exercises into the training programme. These should stimulate the vestibular, proprioceptive, and visual systems in more complex sensory conditions.

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Conflicts of interest

The authors declare no conflicts of interest.

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ORIGINAL ARTICLE

Mental conditioning and pulse oximetry monitoring in short-term training of alpine skiers aged 13–16 years

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

Abstract

Background and Study Aim — Mental conditioning is an important part of modern athletic preparation. It helps regulate arousal, focus, and performance stability. This study examined the psychophysiological effects of a short mental training routine that combined relaxation and sport-specific imagery in junior alpine skiers.

Material and Methods — Fourteen athletes (7 from CSS Gheorgheni; 7 from CSS Baia Sprie) took part in a pre–post observational protocol. The Gheorgheni group performed imagery on a ski simulator. The Baia Sprie group followed the same routine without simulator support. Pulse oximetry (CMS-50F) was used to measure pulse rate (PR, bpm) and oxygen saturation (SpO_2, %) at rest, after relaxation, and during imagery. All recordings were taken under standardized seated conditions to ensure measurement consistency. Repeated-measures ANOVA and non-parametric equivalents (Friedman test, Wilcoxon test) were applied to evaluate within-group changes. Between-group comparisons used t-tests or Mann–Whitney U tests, with significance set at $p < 0.05$.

Results — Descriptive analysis showed that PR consistently decreased after relaxation and increased during imagery. SpO_2 remained within normal limits (96–98%). The simulator group showed a greater increase in PR (+18.5 bpm) compared to the control group (+11.2 bpm). This indicates clear autonomic modulation: parasympathetic activation during relaxation and sympathetic activation during imagery. These trends were consistent across all participants. Statistical tests confirmed significant phase effects for PR ($p < 0.001$), with large effect sizes observed within both groups.

Conclusions — Mental rehearsal produced measurable physiological changes without physical activity. This suggests its role in enhancing athletes' internal regulation. While limited by the small sample, the study supports further research using larger groups and more advanced autonomic measures, such as heart rate variability, to refine mental training protocols in alpine skiing.

Keywords: mental training, alpine skiing, imagery; relaxation, psychophysiology, pulse oximetry, heart rate, oxygen saturation, biofeedback, performance readiness

Introduction

Alpine skiing places unique demands on athletes, requiring precise coordination, rapid decision-making, and continuous adaptation to environmental conditions. This sport involves high-speed movement, unpredictable terrain, and complex technical execution under physical and psychological stress. Maintaining consistent performance in such a setting depends not only on physical preparation but also on the athlete's ability to regulate focus, emotional state, and readiness during competition.

Alpine skiing places unique demands on athletes, requiring precise coordination, rapid decision-making, and continuous adaptation to changing terrain and weather. This high-intensity winter sport combines speed, technical execution, and psychological control under pressure. The complex interaction of physical strain and cognitive load makes skiing especially sensitive to fluctuations in attention, emotional stability, and readiness. Fatigue, fear of mistakes, and unpredictable course

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conditions can impair focus and increase the risk of performance errors or injury. As a result, optimal performance in alpine skiing depends not only on physical preparation but also on mental regulation and psychological conditioning [1, 2, 3].

Mental conditioning, also referred to as mental training, is a structured process through which athletes learn to regulate arousal, focus, and emotional stability. These skills enhance their ability to perform under pressure [4, 5]. Mental training includes a variety of cognitive-behavioral techniques such as goal setting, imagery, relaxation, self-talk, and mindfulness [6]. Numerous studies have shown that these strategies improve attention, confidence, and resilience during competition [7]. For example, Thelwell and Greenlees [3] demonstrated that mental skills training helps endurance athletes maintain consistent performance by enhancing focus and reducing perceived fatigue. Similarly, mindfulness-based interventions have been linked to better emotional regulation, sleep quality, and psychophysiological recovery in elite athletes [8].

In recent years, researchers have increasingly emphasized the integration of mental training into regular technical and tactical preparation routines [9, 10]. Psychological skills training is now considered essential by coaches and sport psychologists for enhancing both mental and physiological performance. It contributes to improved motor learning, motivation, and adaptability [11].

In alpine skiing, mental training plays a particularly important role due to the sport's reliance on anticipation, rhythm, and trajectory planning. Visualization and imagery techniques help skiers mentally rehearse course segments, including gate sequences, pitch transitions, and turning points. This mental rehearsal improves timing, reaction accuracy, and movement economy [12, 13]. According to Joksimovic and Joksimovic [7], imagery in skiing involves a deliberate and structured repetition of mental routines simulating the full course, which promotes more efficient motor programming.

Experimental studies have shown that systematic mental training, especially when combined with neurolinguistic programming (NLP) and relaxation techniques, can improve concentration, confidence, and emotional stability in junior athletes [14, 15, 16]. Grosu and colleagues [14, 16] reported that specific NLP-based routines reduce anxiety and improve attentional control in ski performance. These results are consistent with newer findings indicating that mental rehearsal, when paired with biofeedback, enhances self-awareness and reduces performance variability [17, 18].

The connection between cognitive processes and physiological activation has received growing attention in recent years. During imagery and other mental tasks, the central nervous system reproduces activation patterns similar to those seen during real movement. These processes affect cardiovascular, respiratory, and muscular functions [19, 20]. Functional neuroimaging studies show that motor imagery activates premotor and parietal brain regions involved in movement planning and control [21]. This neural similarity helps explain why mental rehearsal causes measurable changes in heart rate, breathing patterns, and skin conductance, even when no physical movement occurs [22].

Such physiological changes can be tracked with simple, non-invasive instruments and offer useful feedback for athletes and coaches. Pulse oximetry, for example, measures pulse rate (PR) and oxygen saturation (SpO_2), both of which reflect autonomic nervous system activity [23]. Changes in these values indicate shifts between parasympathetic and sympathetic dominance and can act as indirect markers of arousal or relaxation during mental routines [24, 25]. In sports such as alpine skiing, which involve brief, high-intensity efforts lasting 80 to 150 seconds [26], these indicators are especially relevant. Understanding how mental training affects such physiological responses can improve strategies for managing performance readiness and recovery.

The combination of mental training and physiological monitoring offers a promising direction in applied sport science. Previous studies have used biofeedback tools, such as heart rate variability monitors and oximeters, to improve athletes' awareness of internal states [21]. These tools allow real-time visualization of physiological changes and support the development of self-regulation and concentration skills [27]. In alpine skiing, such integration is helpful for managing transitions between relaxation and activation during pre-competition routines. New wearable devices now make it possible to measure psychophysiological responses during or immediately after mental tasks. This enables more accurate tracking of autonomic changes [28, 22].

These developments point to a shift toward individualized, data-based mental preparation. Combining subjective perception with objective physiological data may improve performance control [29]. However, despite the wide use of mental techniques such as imagery and relaxation in skiing, few studies combine these methods with physiological feedback. The use of wearable pulse oximeters to track autonomic responses during mental routines remains underexplored. In addition, little research has compared traditional imagery with embodied formats, such as simulator-assisted rehearsal. This limits current understanding of how mental preparation connects with physiological regulation in winter sports.

Analysis of research findings has shown that mental training improves cognitive control, emotional stability, and psychophysiological readiness in high-performance sports. Authors emphasize that combining psychological strategies with physiological monitoring strengthens the connection between perceived effort and measurable internal responses. At the same time, several aspects of this interaction, including the role of sensor-based feedback and the influence of physical embodiment during mental rehearsal, remain insufficiently addressed in applied contexts. This limitation continues to affect the development of integrated approaches for preparing athletes in sports that require both technical precision and rapid adaptation, such as alpine skiing.

The aim of the present study was to assess the psychophysiological effects of a short mental training protocol that combined relaxation and sport-specific imagery in junior alpine skiers.

The following hypotheses were proposed: (1) Pulse rate (PR) would decrease after relaxation, indicating parasympathetic activation.

(2) PR would increase during imagery, reflecting sympathetic engagement and performance-oriented arousal.

(3) Oxygen saturation (SpO_2) would remain within normal physiological limits (95–99%) and show minor fluctuations inversely related to PR.

Materials and Methods

Participants

Fourteen junior alpine skiers participated in the study, with equal representation from two training clubs: CSS Gheorgheni (n = 7) and CSS Baia Sprie (n = 7). Inclusion criteria included membership in a competitive junior ski team, valid medical clearance for training and testing, and absence of acute illness or injury within the previous four weeks. Exclusion criteria were a history of cardiopulmonary disease, current respiratory infection, or altitude exposure above 1500 meters within 72 hours before testing.

The final sample consisted of 8 males and 6 females, aged 13 to 16 years (mean age: 14.5 ± 0.9 years). All athletes had 3 to 6 years of competitive experience in alpine skiing. Baseline physiological parameters, pulse rate (PR) and oxygen saturation (SpO_2), were within normal limits. No significant differences were observed between groups at the pretest stage.

Parental or guardian consent was obtained for all participants. The study followed the principles of the Declaration of Helsinki and was approved by the institutional ethics committee (protocol code 2025-ALP-MT-01, approval date: 18 February 2025).

Research Design

A two-group repeated-measures design was used. Three standardized phases were conducted on the same day in a fixed sequence: (1) Resting baseline (seated, quiet, 5 minutes) (2) Guided relaxation (grounding and respiratory focus, 8 to 10 minutes) (3) Performance-oriented imagery of a 54-gate descent (8 to 10 minutes)

Both groups followed the same mental routine. The Gheorgheni group performed imagery using a ski simulator (embodied support), while the Baia Sprie group completed imagery without the simulator (control condition).

Each phase was followed by pulse oximetry measurement. The sport context involved a short-duration, high-intensity task typical of junior giant slalom runs, lasting approximately 80 to 150 seconds. All recordings were taken at rest to isolate the psychophysiological effects of the mental routine, and not during physical effort.

The order of phases was fixed to preserve ecological validity, starting with relaxation and ending with imagery. Potential order effects were acknowledged. Within-subject contrasts and descriptive effect sizes were therefore included in the analysis.

All sessions took place in a quiet room at the athletes' training facilities, scheduled at consistent times of day (±1 hour). Participants refrained from consuming caffeine or engaging in vigorous exercise for at least three hours before testing. After a 10-minute seated acclimatization period, the following sequence was conducted:

- Baseline (REST): 5 minutes of seated rest.
- RELAX: 8 to 10 minutes of guided grounding involving breath pacing and body scanning. The audio script was adapted from a published protocol [28].
- IMAGERY: 8 to 10 minutes of guided, sport-specific imagery of a 54-gate descent. The task included first-person perspective, speed modulation, trajectory planning, cueing for hip, knee, and ankle coordination, gate timing, and edge transitions.

The Gheorgheni group completed the imagery phase on a ski simulator using the Dry Skiing Tech framework [29, 30] to simulate trajectory and pressure changes. The Baia Sprie group performed the same imagery task in a seated position. Coaches supervised each session to ensure adherence. No physical activity was performed during data collection.

All participants completed the full mental training sequence. Adherence was confirmed through session checklists signed by supervising coaches. There were no dropouts or protocol deviations during the intervention.

Outcomes and Equipment

The primary outcome was pulse rate (PR, beats per minute), measured using a wrist-worn pulse oximeter (CMS-50F, Contec Medical Systems, Qinhuangdao, China). The secondary outcome was arterial oxygen saturation (SpO_2, percentage), measured with the same device.

Acquisition

After each phase (REST, RELAX, IMAGERY), PR and SpO_2 were recorded for 60 seconds. During measurement, the athlete remained seated with the hand supported at heart level, avoiding movement or speech. The mean value over the 60-second window was used for analysis. All sessions took place at near sea level. Device fit was verified according to the manufacturer's instructions.

Statistical Analysis

All analyses were conducted using IBM SPSS, version 25. Data were screened for outliers and tested for normality using the Shapiro–Wilk test. For within-group comparisons across the three experimental phases (REST, RELAX, IMAGERY), a one-way repeated-measures ANOVA was performed separately for pulse rate (PR) and oxygen saturation (SpO_2). For the control group, only RELAX and IMAGERY phases were compared using a two-level within-subject factor.

Sphericity was assessed using Mauchly's test. When violated, the Greenhouse–Geisser correction was applied. Partial eta squared (η^2) was reported as a measure of effect size. Pairwise comparisons were adjusted using the Bonferroni correction.

To account for the small sample size (n = 7 per group), non-parametric alternatives were also computed. These included the Friedman test with Wilcoxon post hoc comparisons and r as the effect size. Between-group comparisons within each phase were conducted using either independent samples t-tests or the Mann–Whitney U test, depending on distribution. The significance level was set at 0.05 (two-tailed). Where applicable, 95 percent confidence intervals were reported.

Results

All fourteen junior alpine skiers completed the full assessment protocol (Control group: Baia Sprie, n = 7; Experimental group: Gheorgheni, n = 7). Descriptive statistics for pulse rate (PR) and arterial oxygen saturation (SpO_2) are presented in Tables 1 and 2.

Table 1. Pulse rate (PR) and oxygen saturation (SpO_2) in the control group (Baia Sprie, n = 7)

Phase	PR (bpm), Mean ± SD	SpO_2 (%), Mean ± SD
Relaxation	60.1 ± 3.4	97.9 ± 0.3
Imagery	71.3 ± 4.0	97.4 ± 0.3

Note: The increase in PR from relaxation to imagery was statistically significant ($F(1,6) = 22.84$, $p < 0.001$, partial eta squared = 0.79). No significant change was observed in SpO_2 ($p > 0.05$).

Table 2. Pulse rate (PR) and oxygen saturation (SpO_2) in the experimental group (Gheorgheni, n = 7)

Phase	PR (bpm), Mean ± SD	SpO_2 (%), Mean ± SD
Rest	64.6 ± 4.8	97.4 ± 0.6
Relaxation	58.1 ± 4.3	97.8 ± 0.5
Imagery	76.6 ± 4.9	96.8 ± 0.5

Note: Pulse rate decreased significantly during relaxation and increased sharply during imagery ($F(2,12) = 34.72$, $p < 0.001$, $\eta^2 = 0.85$). No significant changes were observed in SpO_2 ($p > 0.05$).

In the control group (Baia Sprie, imagery without simulator), the mean pulse rate after relaxation was 60.1 ± 3.4 beats per minute. During performance-oriented imagery, this value increased to 71.3 ± 4.0 beats per minute. The change represented an average increase of 11.2 beats per minute, corresponding to an 18.6 percent rise from the relaxation to the imagery phase. Oxygen saturation remained within normal physiological limits, with a small decrease from 97.9 ± 0.3 percent to 97.4 ± 0.3 percent (change = −0.5 percentage points). Both trends were consistent across all seven participants, suggesting a stable psychophysiological response during the imagery phase.

The imagery phase elicited a significant PR increase [$F(1,6) = 22.84$, $p < 0.001$, $\eta^2 = 0.79$] and a minimal, non-significant decrease in SpO_2 ($p > 0.05$), as shown in Figure 1.

In the experimental group (Gheorgheni, imagery with simulator), pulse rate was measured across three standardized phases: resting baseline, relaxation, and imagery. At rest, the mean pulse rate was 64.6 ± 4.8 beats per minute. After relaxation, it decreased to 58.1 ± 4.3 beats per minute. This represents a reduction of 6.5 beats per minute, or 10.1 percent. During the imagery phase, pulse rate rose to 76.6 ± 4.9 beats per minute. This increase of 18.5 beats per minute from the relaxation phase corresponds to a 31.8 percent change.

Oxygen saturation showed minor, non-clinically relevant fluctuations. The values were 97.4 ± 0.6 percent at rest, 97.8 ± 0.5 percent after relaxation, and 96.8 ± 0.5 percent during imagery. From relaxation to imagery, the average decrease was 1.0 percentage point. This within-subject pattern, characterized by a decrease in pulse rate during relaxation, an increase during imagery, and a small reduction in oxygen saturation, was observed consistently in all seven athletes (Table 2; Figure 2).

PR decreased during relaxation and increased sharply during imagery, while SpO_2 remained within normal physiological limits, as shown in Figure 2. This response pattern was observed consistently across participants and reflects the transition from parasympathetic recovery to task-related

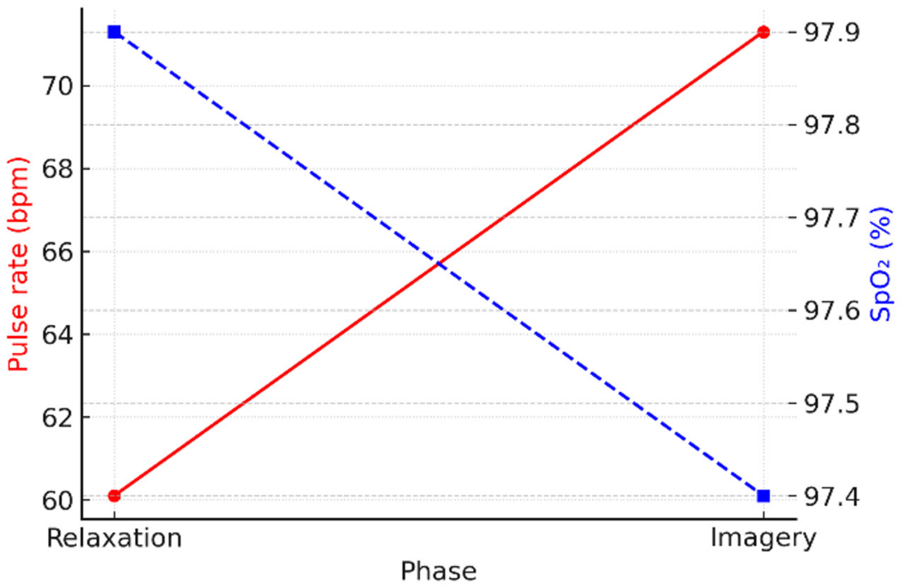

Figure 1. Mean pulse rate (PR, bpm) and oxygen saturation (SpO_2, %) across the two phases (Relaxation, Imagery) in the Baia Sprie control group (n = 7)

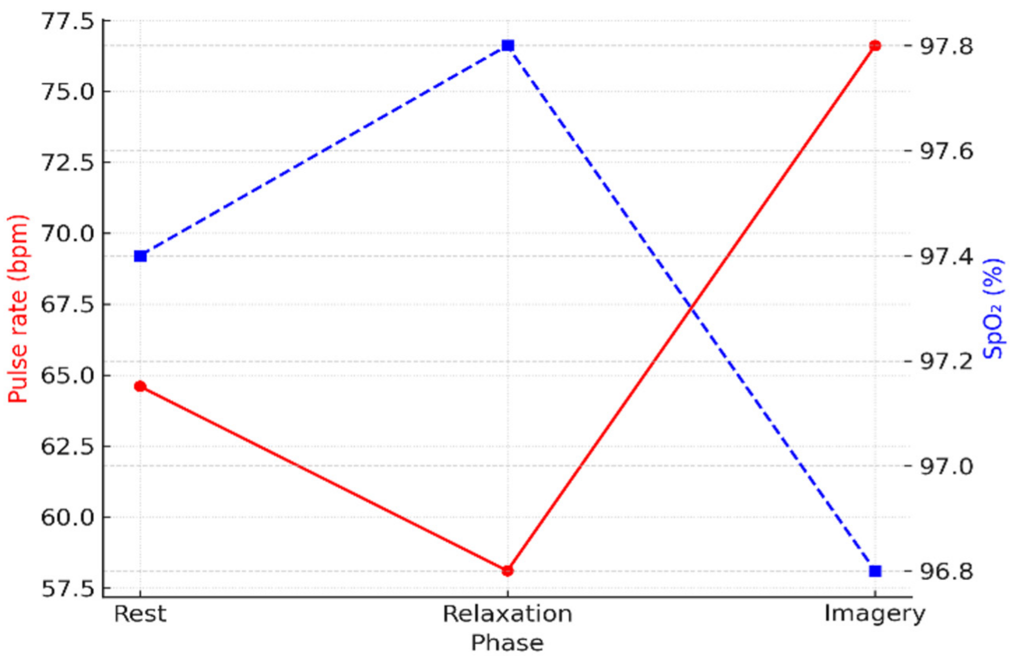

Figure 2. Mean pulse rate (PR, bpm, red line) and oxygen saturation (SpO_2, %, blue line) across the three phases (Rest, Relaxation, Imagery) in the Gheorgheni experimental group (n = 7).

sympathetic activation, with minimal respiratory fluctuation.

Pattern consistency and group contrast

Both groups demonstrated the expected psychophysiological pattern. The relaxation phase was associated with a reduction in pulse rate, while performance-oriented imagery led to an increase. Throughout all phases, oxygen saturation remained within the typical resting range (approximately 96 to 98 percent). The magnitude of the pulse rate increase from relaxation to imagery was greater in the simulator-assisted group. Specifically, the experimental group showed a rise of 18.5 beats per minute, compared to 11.2 beats per minute in the control group. This difference suggests that simulator-based imagery may enhance embodiment and task engagement more effectively than imagery without simulator support.

Analytic note

Due to the small sample size and pilot design of the study, all findings are interpreted as descriptive and exploratory. Nevertheless, the direction and consistency of effects across all participants align with established physiological responses: a parasympathetic shift during relaxation and sympathetic activation during imagery. These preliminary findings provide a rationale for future studies with larger samples and confirmatory designs.

Discussion

This pilot study examined the short-term psychophysiological effects of a mental training protocol that combined relaxation and sport-specific imagery in junior alpine skiers. The main findings indicate that relaxation was associated with a decrease in pulse rate, while imagery led to a pronounced increase. These changes reflect modulation of autonomic activation. Oxygen saturation remained within normal physiological limits and showed only minor fluctuations, which were inversely related to pulse rate. The pattern was consistent across participants, with a greater magnitude of change observed in the group using a ski simulator during imagery.

These results support the hypothesis that mental routines can influence physiological activation, even in the absence of physical effort. The present study extends earlier work by Grosu et al. [14, 16] by introducing a dual-condition design (imagery with and without simulator use) and incorporating physiological markers of autonomic activity. In contrast to previous studies that focused mainly on cognitive-behavioral strategies or neuro-linguistic programming, the current protocol included objective physiological feedback. This integration reflects a shift toward embodied cognitive training in sport.

The opposite trends in pulse rate and oxygen saturation observed during relaxation and imagery reflect coordinated modulation of the autonomic nervous system. A decrease in pulse rate after relaxation is typically associated with parasympathetic dominance and reduced psychophysiological arousal. In contrast, the increase in pulse rate during motor imagery corresponds to sympathetic activation and anticipatory effort preparation. These physiological changes are well-documented indicators of mental engagement in athletes. Mental imagery frequently induces cardiovascular and respiratory adjustments that resemble those produced by actual movement. The slight decline in oxygen saturation during imagery may reflect an increased metabolic demand or subtle respiratory changes linked to focused concentration, rather than a true physiological desaturation.

Pulse oximetry offers a simple and non-invasive method for tracking autonomic activation, but its sensitivity to specific branches of the autonomic system is limited. Future studies should include additional physiological markers, such as heart rate variability, which more accurately reflect parasympathetic modulation. Prior research in endurance sports has established heart rate variability as a reliable measure of mental workload, recovery, and autonomic balance. Applying such multimodal monitoring in alpine skiing could enhance the interpretation of psychophysiological responses to mental training. Comparative validation using heart rate variability or electrodermal activity would further clarify the reliability of pulse rate and oxygen saturation as surrogate indicators of internal state regulation.

The findings are consistent with previous studies showing that imagery-based interventions enhance motor readiness, confidence, and psychophysiological synchronization between central and peripheral systems [17, 18, 19, 21, 22, 28]. This body of research demonstrates that vivid imagery can induce measurable autonomic changes and promote perceptual–motor coupling, contributing to improved performance. The greater physiological response observed in the simulator-assisted group suggests that additional proprioceptive and visual constraints may strengthen sensorimotor integration. This interpretation aligns with effect-oriented models of action control and neural efficiency in trained athletes [21, 22, 27, 28, 29].

These findings describe how short mental routines can influence autonomic activity in sport-specific settings. The consistent physiological responses observed in both groups suggest that structured imagery and relaxation exercises affect internal regulation without physical effort. This supports the relevance of including both cognitive and sensorimotor components when examining psychophysiological responses in preparation for performance.

Limitations and Future Directions

Although the present findings offer preliminary insights, several methodological limitations should be considered. The study involved a small sample of junior skiers, which limits statistical power and restricts the generalizability of the results to other competitive levels or age groups. The short-term design, based on single-session measurements, did not allow for evaluation of long-term adaptations or retention effects. In addition, only pulse rate and oxygen saturation were assessed. Including other autonomic indicators, such as heart rate variability, electrodermal activity, or respiratory rate, would provide a more complete profile of psychophysiological regulation.

Future studies should recruit larger and more diverse samples, ensure balanced gender representation, and conduct repeated assessments across multiple training sessions. Combining physiological monitoring with psychological variables such as perceived exertion, mental workload, and attentional focus may help clarify the mechanisms linking mental rehearsal with autonomic control and performance outcomes [30, 31, 32]. The use of wearable biofeedback devices and immersive simulation technologies may further increase ecological validity and support individualized development of mental conditioning protocols in alpine skiing and other high-demand sports.

Practical Applications

The results of this study emphasize the practical value of combining mental conditioning with simple physiological monitoring in regular ski training. Short sessions incorporating relaxation and imagery can assist athletes in regulating arousal, maintaining attentional control, and improving self-awareness before competition. Wearable devices such as pulse oximeters offer coaches and sport psychologists objective, non-invasive measures of physiological activation (pulse rate, oxygen saturation) that complement subjective indicators of readiness or anxiety.

For coaching practice, guided relaxation and sport-specific imagery can be integrated into warm-up or recovery protocols to improve athletes' ability to transition between recovery and activation states. These routines are easily adaptable to different phases of technical preparation, such as visualizing gate sequences, timing turns, or simulating descent rhythm. In addition, feedback from physiological sensors may facilitate individualized monitoring of training load, allowing for more precise adjustments in both physical and psychological preparation [33, 34, 35].

Overall, this approach supports the implementation of biofeedback-informed mental training as a practical and cost-effective strategy to optimize focus, stress regulation, and performance consistency in alpine skiing and other technically demanding, high-intensity sports.

Conclusions

The findings of this pilot study demonstrate that short sessions of mental training can elicit measurable psychophysiological responses in junior alpine skiers. The relaxation phase was associated with a decrease in pulse rate, while the subsequent imagery phase produced a marked increase in cardiac activation. Oxygen saturation remained stable within normal physiological limits throughout the procedure. These results indicate that mental rehearsal modulates autonomic regulation even in the absence of physical effort.

Although exploratory in nature, the present findings suggest that combining relaxation–imagery sequences with pulse oximetry monitoring may offer a useful form of biofeedback to support focus, readiness, and emotional regulation in young athletes. The enhanced response observed in the simulator-assisted group supports the use of embodied imagery tools in alpine skiing as a means of reinforcing task realism and sensorimotor integration.

This pilot study contributes preliminary but consistent evidence that mental conditioning is a viable strategy for improving psychophysiological control and performance stability in alpine skiing. By integrating psychological training with physiological feedback, the approach supports a more holistic model of athlete development.

Unlike previous research focused exclusively on cognitive routines, this study introduces a combined mental and sensory training paradigm that incorporates wearable oximetry and ski simulation. This model represents a scalable and practical framework for embodied self-regulation training in youth alpine skiing.

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The authors thank Mr. Vlad Teodor Grosu for his collaboration. The present study forms part of the doctoral research conducted by the first author. The applications of mental training in sports span multiple domains. The integration of sports science (in this case, alpine skiing), psychology, statistics, and sensor-based technology contributes to the development of objective and interdisciplinary research.

Conflict of Interest

The authors declare no conflict of interest.

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ORIGINAL ARTICLE

Comparative analysis of goniometric indicators of kettlebell lifting and arm wrestling athletes

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

Abstract

Background and Study Aim The examination of athletes' physical condition is an essential component of sports monitoring. Flexibility is a key physical quality in sport, and goniometry is widely used to assess it. However, goniometric indicators are rarely applied to evaluate kettlebell lifting athletes. The aim of this study was to compare the range of movements in the hand joints of kettlebell lifting (KL) and arm wrestling (AW) athletes using goniometric testing.

Material and Methods Thirty-six athletes participated in the study, including 21 KL athletes and 15 AW athletes matched by age and skill level. The range of active movements in the wrist, elbow, and shoulder joints was measured using an IGaging electronic goniometer (USA). Flexion, extension, abduction, and adduction were assessed. For each movement, the maximum value of two or three attempts was recorded. Asymmetry coefficients were calculated, and group differences were analyzed using the Rosenbaum (Q) criterion.

Results KL athletes demonstrated a greater range of movements in most wrist and shoulder joint indicators. AW athletes showed a greater flexion range in the right elbow joint. Significant asymmetry was observed in KL athletes, particularly in wrist extension, wrist adduction, elbow extension, and several shoulder movements. In AW athletes, asymmetry was less pronounced and detected mainly in wrist abduction and adduction.

Conclusions The study established clear differences in joint mobility between kettlebell lifting and arm wrestling athletes. KL athletes exhibited greater joint mobility and more pronounced asymmetry, reflecting the specific demands of kettlebell lifting. AW athletes showed increased elbow flexion associated with arm-wrestling technique. Goniometry is an objective and informative method for assessing athletes' functional condition and may be used as a screening tool for monitoring KL and AW athletes.

Keywords: kettlebell lifting, arm wrestling, amplitude, movements, joints, goniometric, research, asymmetry.

Introduction

Research and analysis of the condition of athletes is a mandatory and important component of sports monitoring. This information allows for the optimization of training, the prediction of athletes' success, and the assessment of their level of preparedness. The main objective of this study is to investigate basic physical qualities, such as strength, endurance, speed, coordination, and flexibility. The qualities selected for assessment depend on the specific impact of the sport on the athlete's body.

Flexibility is one of the most important physical qualities in sports and physical culture. It determines the possibility of achieving success in many sports [1, 2, 3, 4]. It is a criterion for the effectiveness of fitness training [5]. Flexibility also allows for the assessment of recovery and rehabilitation effectiveness [6, 7, 8]. The comparison of flexibility indicators provides information about the functional state of athletes, amateurs, and people undergoing rehabilitation. Goniometry is the leading method for studying flexibility [9, 10, 11]. Goniometric indicators are used to assess the preparedness of athletes and to evaluate the effectiveness of rehabilitation after injuries [6].

In a previous study [12], goniometry was used to assess the functional state of the musculoskeletal system of athletes during a year-long training cycle. Low flexibility and joint mobility reflected insufficient musculoskeletal system elasticity. This indicated overexertion in the bodies of the athletes. Positive dynamics were interpreted as evidence of functional state restoration.

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Flexibility indicators are interrelated with other criteria of the condition of athletes [13, 14]. A previous study [13] examined the relationship between flexibility and injury history when performing strength endurance exercises, such as running, cycling, swimming, and triathlon. Flexibility was assessed using goniometry. Significant correlations were observed. It was concluded that flexibility can influence injury characteristics. This relationship varies depending on the focus of strength training.

A comparative analysis of the morphofunctional characteristics of athletes in various martial arts as factors of success has also been conducted [15, 16]. Goniometric characteristics were assessed as predictors of success in wrestling and striking martial arts. The range of movements reflects the ability to perform an effective grab, strike, or block.

A similar design was used in another study [7]. A set of morphofunctional indicators was applied to assess the recovery of basketball players. Goniometry was used to measure the range of movements of the joints, and muscle testing was used to determine muscle strength. Comparative measurements of muscle parameters and personalized tests adapted for each athlete were performed. An increase in the range of movements in the joints was interpreted as an optimization of the athletes' condition.

Goniometric indicators were included in a set of tests to assess the condition of sport dancers [3]. The authors used the Columbia Adolescent Dancer Screening (CADS). The questionnaire included information about dance injuries, health questionnaires, and tests to assess aerobic capacity, range of movements, strength, balance, and dance technique. The pragmatism, evidence base, and effectiveness of the screening methods used were confirmed.

The correlations among flexibility, muscle strength, and static and dynamic balance were studied by Unuvar et al. [17]. Differences in these indicators were found between athletes and non-athletes. The data were interpreted as the result of the influence of regular physical activity.

A similar design was used in a previous study [11]. Asymmetries and correlations between the strength and flexibility of the knee flexors and extensors in young football players were examined. The existence of dependencies between muscle strength and flexibility was confirmed.

Another study [14] showed that specific loads in handball affect the shoulder joint condition of athletes. Insufficient muscle strength reduces the range of movements and increases the risk of injury. It was concluded that including exercises to strengthen the rotator and adductor muscles in the training plan can improve shoulder health in handball players.

Goniometric studies can be used to assess limb asymmetry [18, 19, 20, 21]. This is important for analyzing and predicting sports performance and for preventing injuries. Sports asymmetry is defined as bilateral differences in the fitness parameters of athletes. These asymmetries are likely a function of the dominant limb and are intensified by long-term sports experience.

Goniometric indicators are important for achieving success in strength sports. The range of movements in the shoulder, hip, and knee joints of female powerlifters was evaluated in the study by Spence et al. [22]. An increase in the range of movements in the shoulder joint was found compared with female amateurs.

In the study by Podrigalo et al. [23], a goniometric assessment of the range of movements in the joints of the hands of arm wrestling (AW) athletes and amateurs was conducted. The range of movements in the hand joints was examined. The results suggest that the range of movements in the joints is an important factor for AW performance. An increase in the indicators confirms the optimization of flexibility in athletes compared with amateurs. The results also reflect the expansion of the arsenal of technical wrestling techniques. This allows for improved performance.

Analysis of research findings has shown that flexibility and goniometric indicators are informative parameters for assessing the functional state of athletes in various sports. Researchers emphasize that the range of movements in the joints is closely related to physical preparedness, recovery processes, and the risk of injury. At the same time, authors highlight that joint mobility reflects sport-specific demands and can influence technical performance. However, goniometric indicators are practically not used to assess the condition of kettlebell lifting (KL) athletes. Some studies have proposed a set of tests to assess the condition of KL athletes [24]. However, the goniometric method was not used in this battery of tests. These aspects indicate the need for further analysis of joint mobility in strength disciplines and demonstrate the relevance of examining sport-specific movement characteristics.

Research hypothesis

The available results allowed us to develop the following research question: "Will the specifics of kettlebell lifting and arm wrestling training affect the range of movements in the joints of the upper limbs?"

The research hypothesis was to identify differences in the range of movements in the hand joints in KL and AW athletes. The results of the analysis will make it possible to optimize the training of athletes in these sports and to use goniometric studies to monitor their condition.

Based on the above, this study aimed to conduct a comparative analysis of the range of movements in the joints of the hands in kettlebell lifting and arm wrestling athletes based on the results of goniometric testing.

Materials and Methods

Participants

The study used the test results of 36 kettlebell lifting and arm wrestling athletes. The participants were divided into groups according to the sport. Group 1 included 21 kettlebell lifting athletes with an average age of 21.57±2.11 years and skill levels ranging from beginners to International Masters of Sport. Group 2 included 15 arm wrestling athletes with an average age of 21.80±0.49 years and skill levels from beginners to Masters of Sport. Differences in age were insignificant ($p > 0.05$).

Inclusion/exclusion criteria. The inclusion criteria were no injuries in the last 6 months and no medication intake in the last month. The interval between testing and the last training session was 24 h.

The study program and design were discussed and approved at a meeting of the Bioethics Committee of the Kharkiv State Academy of Physical Culture (Protocol No. 14 of September 16, 2025). All participants or their legal guardians provided written informed consent in accordance with the Declaration of Helsinki. Participant data were stored anonymously in a database to ensure confidentiality.

Study Design

The amplitudes of active movements were determined using an IGaging electronic goniometer (USA) in the wrist, elbow, and shoulder joints of the arms. The results were expressed in angular degrees. Flexion, extension, abduction, and adduction at the wrist and shoulder joints were assessed. Flexion and extension at the elbow joints were also assessed. Two or three measurements of the same movement were taken, and the maximum values were recorded. The measurements posed minimal risk and were non-invasive to health.

Testing Procedure. All measurements were performed in a standardized standing position with the arms relaxed along the body. The right arm was tested first, followed by the left arm. Each joint movement was assessed in the anatomical plane corresponding to the direction of motion, while compensatory movements of adjacent joints were visually controlled and minimized. Participants were given one adaptation trial before the measurements to familiarize themselves with the procedure. No warm-up exercises were permitted to avoid artificially increasing joint mobility. All tests were conducted indoors under identical environmental conditions. Two or three repeated measurements were obtained for each movement, and the maximum value was used for analysis. All assessments were performed by the same specialist with experience in goniometric testing to ensure consistency of the measurements.

Equipment. A digital IGaging electronic goniometer (USA) was used for all measurements. The device has a measurement range from 0 to 360 degrees and a digital display with a resolution of 0.1 degrees. The goniometer was calibrated according to the manufacturer's recommendations before each testing session. The measurement accuracy and stability of the device have been confirmed in previous studies [15, 23], allowing its use for research tasks requiring objective joint mobility assessment.

Examiner Qualifications. All goniometric measurements were performed by the same examiner. The examiner had specialized training and practical experience in conducting joint mobility assessments in athletes. The use of a single qualified examiner minimized measurement variability and ensured procedural consistency throughout the study. Prior to the study, the examiner completed additional practice sessions to standardize measurement technique and adherence to testing protocol.

Participant Characteristics. All athletes reported right-hand dominance. The determination of limb dominance was based on self-report and confirmed through sport-specific tasks. The assessment of dominance was required to correctly interpret joint asymmetries and to ensure consistency during testing. The training experience of the participants was recorded. Kettlebell lifting athletes had an average training experience of 3 to 7 years, depending on their qualification level. Arm wrestling athletes demonstrated a similar range of training experience. All participants were actively training and participating in competitions at the time of the study. Their training routine included at least three structured training sessions per week. These characteristics were considered important for interpreting joint mobility and asymmetry patterns, as training experience and limb dominance influence the development of flexibility and strength adaptations in both sports.

Standardization of Testing Conditions. All measurements were conducted under standardized conditions. Testing took place indoors in a quiet laboratory environment at a controlled room temperature of 21–23°C. The measurements for all participants were performed at the same time of day, in the afternoon hours, to minimize the influence of circadian variability on joint mobility. Participants were instructed to refrain from intensive physical activity for 24 hours before testing. They were also asked to avoid consuming stimulants, such as caffeine, on the day of testing. Compliance with these requirements was verified verbally prior to the assessment. Before the measurements, participants remained seated for 5 minutes to stabilize physiological parameters. No additional stretching or warm-up procedures were allowed, as these could artificially increase joint mobility. All conditions were identical for both groups to ensure methodological consistency.

Statistical analysis

Data analysis was performed using licensed MS Excel 2019 version 2506. The nature of the distribution and the size of the groups determined the use of the median and the first (25 percent) and third (75 percent) quartiles. The nonparametric Rosenbaum (Q) criterion was used to assess differences between groups, with differences considered significant at p<0.05. The asymmetry coefficients for the movements studied were calculated using the following formula [25]:

$$SI = \frac{X_r - X_l}{0.5 \times (X_r + X_l)} \times 100\%$$

In this formula, Xr represents the value for the right side, and Xl represents the value for the left side. A value of zero indicates perfect symmetry in the analyzed joints. A positive SI value means that Xr is greater than Xl, while a negative value indicates that Xr is lower than Xl [26]. Asymmetry is considered present when the SI exceeds 10 percent [27].

Results

The obtained results are presented in Tables 1 and 2.

Table 1 confirms the differences in the range of movements in the athletes' hand joints. An increased range of movements was found in kettlebell lifting athletes in the right (Q=20, p<0.01) and left (Q=17, p<0.01) wrist joints. The range of movements in the right elbow joint was greater in AW athletes (Q=7,

Table 1. Amplitude of movements in hand joints of kettlebell lifting and arm wrestling athletes (All values are presented in degrees)

Indicators	1 Group			2 Group		
	1st quartile	Median	3rd quartile	1st quartile	Median	3rd quartile
Right wrist joint						
Flexion	66.8	69.4	77.6	67.0	72.0	73.5
Extension	49.0	60.72	67.3	48.0	52.0	56.5
Abduction	39.1	43.52	49.8	40.5	42.02	49.5
Adduction	38.7	47.61	55.9	26.5	33.02	36.5
Right elbow joint						
Flexion	115.8	124.91	130.6	119.0	125.02	132.5
Extension	20.9	23.42	26.9	17.0	19.02	24.0
Right shoulder joint						
Flexion	192.0	195.91	203.0	153.5	159.0	170.0
Extension	69.8	80.21	87.6	45.0	55.0	60.5
Abduction	182.9	200.61	206.9	139.0	148.0	162.0
Adduction	30.3	38.82	45.2	16.5	20.0	27.5
Left wrist joint						
Flexion	64.3	69.3	81.9	65.0	69.0	72.0
Extension	61.1	66.8	73.7	54.5	59.0	62.5
Abduction	42.3	51.3	59.5	39.0	41.0	53.0
Adduction	40.4	54.11	67.0	29.5	33.0	37.0
Left elbow joint						
Flexion	125.3	137.0	156.2	124.0	129.0	133.0
Extension	25.1	27.71	35.1	18.0	20.0	23.0
Left shoulder joint						
Flexion	162.8	176.8	184.3	155.0	163.0	170.5
Extension	65.9	76.81	84.9	48.5	54.0	60.5
Abduction	164.4	178.1	187.6	143	148.0	158.0
Adduction	35.2	44.1	47.5	20	24.0	25.5

Note. 1 – differences between groups are significant (p<0.05), 2 – differences with the left hand are significant (p<0.05).

Table 2. Coefficients of asymmetry of the range of movements in the hand joints of kettlebell lifting and arm wrestling athletes.

Indicators	1 Group			2 Group		
	1st quartile	Median	3rd quartile	1st quartile	Median	3rd quartile
Wrist joint						
Flexion, %	-11.93	-1.32	11.34	-1.41	4.26	9.94
Extension, %	-26.70	-13.42	-3.07	-12.68	-8.40	-6.85
Abduction, %	-20.22	-8.68	-3.64	-8.66	-2.30	8.70
Adduction, %	-26.49	-16.67	1.62	-21.98	-6.45	2.78
Elbow joint						
Flexion, %	-22.82	-8.66	4.38	-2.28	0.74	1.62
Extension, %	-43.14	-19.91	-7.41	-8.31	0.00	6.06
Shoulder joint						
Flexion, %	4.43	12.89	16.11	-1.18	0.00	0.64
Extension, %	-22.17	1.11	19.12	-6.10	-3.03	2.00
Abduction, %	7.98	11.06	18.87	-3.64	2.31	4.91
Adduction, %	-27.43	-13.72	9.36	-26.61	0.00	4.60

$p<0.05$). The range of movements in the left elbow joint was greater in kettlebell lifting athletes (Q=12, $p<0.01$). The range of movements in the shoulder joints was significantly greater in kettlebell lifting athletes ($p<0.01$). This was confirmed for flexion (Q=25), extension (Q=25), and abduction (Q=24) of the right joint, and for extension (Q=20), abduction (Q=15), and adduction (Q=15) of the left joint. Asymmetry in the range of movements of the hand joints was observed in kettlebell lifting athletes. The range of extension in the wrist joint was smaller in the right hand (Q=9, $p<0.05$). The range of adduction in the wrist joint was greater in the left hand (Q=7, $p<0.05$). Asymmetry was also confirmed in the elbow joint for extension. The range of this movement was greater in the left hand (Q=10, $p<0.01$). The amplitudes of flexion and abduction were greater in the right shoulder joint, with Q=8 ($p<0.05$) and Q=9 ($p<0.05$). The adduction amplitude was greater in the left shoulder joint (Q=7, $p<0.05$). The asymmetry of the range of movements in the arm joints was less pronounced in the arm wrestling athletes. The ranges of abduction and adduction of the wrist joint were smaller in the right hand in both cases (Q=6, $p<0.05$).

Table 2 shows the coefficients of asymmetry of the range of movements. Table shows that the left joint range of movements is greater in kettlebell lifting athletes. This is confirmed by the negative values of all asymmetry coefficients, except for the shoulder joint extension indicator. Significant asymmetry was observed when the coefficient exceeded 10 percent in 6 of 10 cases. These include extension and adduction of the wrist joint, elbow joint extension, and shoulder joint flexion, abduction, and adduction. The asymmetry coefficient confirms the results obtained using the Rosenbaum index. In AW athletes, the asymmetry coefficient did not exceed 10 percent for any movement. This indicates that the range of movements in the joints of the hands is close to symmetry. The asymmetry coefficients for abduction and adduction of the wrist joint were the highest, although they did not exceed 10 percent. Asymmetry in these movements was confirmed using the Rosenbaum index.

Discussion

The purpose of this study was to compare the range of movements in the hand joints of kettlebell lifting and arm wrestling athletes based on goniometric testing. The results showed clear differences between the groups. Kettlebell lifting athletes demonstrated a greater range of movements in most joints, including the wrist, elbow, and shoulder joints. Arm wrestling athletes showed a greater flexion range only in the right elbow joint. The analysis also revealed pronounced asymmetry in kettlebell lifting athletes, while in arm wrestling athletes the range of movements was closer to symmetry.

These findings should be considered in the broader context of sports science and the functional demands of different strength disciplines. A comparative analysis of the physical qualities of athletes in different sports allows us to establish the specific effects of sports loads on the bodies of athletes [9]. This is very important for optimizing sports training, predicting success, and understanding the dynamics of athletic skill.

The choice of the range of movements as the study object reflects the specific impact of sports on the bodies of athletes. The range of movements in the hand joints should be assessed as a predictor of KL success. Sufficient flexibility combined with strength allows the kettlebell to be lifted along the optimal trajectory. This ensures the functionality of KL athletes and increases their performance. The range of movements is also important in AW, as optimal arm movement allows the athlete to win a fight, and sufficient flexibility allows participation under various technical conditions.

Goniometry was selected as the research tool. It is widely used in sports, fitness, and rehabilitation. The advantages of this method include objectivity, simplicity, clarity, and ease of practical application [9, 10, 11]. The instrument used, a digital goniometer from IGaging (USA), allows for quick and objective assessment of the range of movements in the joints. Its effectiveness has been confirmed in previous studies [15, 23].

A significant advantage of goniometry is its ability to assess the impact of specific loads on the bodies of athletes. The tasks of athletes in KL and AW differ, which determined the differences established in the joint range of movements. This agrees with the available literature. The effect of baseball throws on the range of movements in the shoulder joint was evaluated in the study by Reinold et al. [28]. A significant increase in external shoulder rotation was observed immediately after throwing weighted balls. This effect increased as the weight of the balls increased.

The design used in this study, which compares athletes from different sports, is common in scientific research [1, 2, 4, 6]. For example, the flexibility indicators of tennis players and athletes from other sports were compared in the study by Chandler et al. [1]. The results confirmed the specific influence of the sport on the bodies of athletes. Tennis players had a higher external rotation of the shoulder joints. This was due to the nature of their movements. The differences in flexibility indicate adaptation to the musculoskeletal requirements of the sport.

The participants represented sports with a pronounced focus on strength. However, flexibility indicators are important in both sports. The nature of physical activity influenced the flexibility of the athletes. The activity of KL athletes is aerobic, with weights being lifted for 10 minutes. This causes a significant increase in the load on the musculoskeletal system. AW is characterized by predominantly anaerobic exercise, with a bout duration not exceeding 1 minute. The nature of the effort is mixed, combining static and dynamic components.

A similar study design was used in the study by Podrigalo et al. [15]. That study aimed to conduct a comparative goniometric analysis of the range of movements in the hand joints of martial art athletes. The differences reflected the specificity of the martial arts studied. The ranges of abduction and adduction in the right wrist joint and the range of abduction in the left wrist joint were greater in wrestlers. This was interpreted as a reflection of the effective grip required to perform the technique. Strike martial artists had greater left wrist joint extension, right elbow joint flexion, and right shoulder joint extension and abduction. These characteristics demonstrate the ability to deliver strikes.

A similar approach was used in the present study. Differences in the range of movements of KL and AW athletes were assessed considering the specific characteristics of each sport. In KL, kettlebells are lifted with active participation of the wrist joint. Movements in this joint allow the athlete to choose a comfortable position for placing the kettlebell at all stages of the lift. This contributes to an increase in the range of movements.

Hand-to-hand combat requires the initial fixation of the hand position. The position of the wrist joint is one of the most important factors for achieving victory in combat. Rigid fixation of this joint allows the athlete to impose their tactics on the opponent, which increases the likelihood of success. These features result in smaller ranges of movements in the wrist joint in AW athletes.

Differences in the range of movements in the elbow joint also illustrate the characteristics of movements in KL and AW. The left elbow joint had a greater range of extension in KL athletes. This is due to the peculiarities of weightlifting. This movement requires maximal joint extension and stable fixation.

The elbow joint performs an important function in AW. Hand movements are mainly performed by bending the arm. AW athletes use this movement to the maximum during a fight. Therefore, the range of flexion is significantly greater in AW athletes.

The most pronounced differences were found in the shoulder joint movements. Studying the range of movements in this joint is important in many sports. In team sports, these indicators determine the ability to throw a ball. The range of movements in the shoulder joints of handball and volleyball athletes was evaluated in comparison with a control group in the study by Benda et al. [2]. An increase in the range of movements of the dominant arm in extension, horizontal adduction, and external rotation was confirmed in game sport athletes. Asymmetry in shoulder joint extension and external rotation was also found in volleyball and handball athletes.

Another study [4] compared the shoulder range of movements in volleyball, handball, swimmer, and judoka athletes. It was concluded that increasing training volume affects performance, increases the risk of disorders, and can lead to injuries.

Raising the arms above the head is an important technical element in many sports. This increases the requirements for the range of movements in the shoulder joint. Assessing its amplitude allows analysis of the adaptation characteristics of athletes. This approach was used in a previous study [29] to examine the condition of beach volleyball athletes. The absence of asymmetry in shoulder joint movements and the presence of moderate adaptation to exercise loads were demonstrated.

The results obtained confirm the existing literature data. The range of movements in the shoulder joint was significantly greater in kettlebell lifting athletes. This is due to the biomechanics of movement in KL. Lifting kettlebells requires active participation of the shoulder joints. The maximum load is placed on these joints during the jerk exercise.

During a bout in AW, the shoulder joint is more fixed. Athletes perform the movement with their entire body and try to press the opponent's arm against the table. Therefore, the range of movements in the shoulder joints differs significantly between KL and AW athletes. For kettlebell lifting athletes, maximal range is required to provide the optimal trajectory of the lift. For AW athletes, sufficiently rigid fixation of the joint is needed to form a stable kinesthetic chain.

A comparison of the ranges of movements in the right and left joints was performed to identify asymmetry. This parameter is important for assessing the condition of athletes [25, 27, 30, 31]. Asymmetry can lead to dysfunction of the entire body, including the main joints. Goniometric measurements serve as diagnostic and analytical tools. Improved movement symmetry in the joints may indicate the restoration of joint neutrality. Anatomical alignment increases neuromechanical efficiency and kinesthetic control of multidirectional movements. This is necessary to improve athletic performance.

Bilateral measurements of the range of movements in the hand joints were used to assess asymmetry. This approach is consistent with the available literature. The review by Bishop et al. [32] summarizes data on asymmetry assessment in athletes. It is recommended that bilateral tests be used. An important aspect of such studies is the standardization of methodology and analysis to optimize the interpretation of the results obtained.

The results presented in Tables 1 and 2 confirm the presence of asymmetry in the range of movements in the hand joints. This condition was significantly more pronounced in KL athletes. Asymmetry of movement in the shoulder joints of kettlebell lifting athletes was found in 3 of 4 movements. This further confirms the importance of these joints for kettlebell lifting.

The study of asymmetry is an important area of sports science. Different points of view exist regarding the influence of asymmetry on the condition of athletes. The review by Gao et al. [18] examined the features of bilateral asymmetry in competitive sports and the possibility of using asymmetry to assess performance and rehabilitation effectiveness after injuries. Asymmetry can have a positive effect on physical performance in sports where the primary load is placed on the upper limbs.

Other studies [19, 20] have provided data indicating the negative impact of asymmetry. Asymmetry in strength indicators negatively affected the results of change-of-direction performance, sprinting, kicking, and cycling tests [19]. Further research is needed to better understand the influence of strength and power asymmetry on athletic performance. The use of sport-specific tests is particularly important.

Morphological asymmetry can also affect athletic performance [20]. It can cause adverse functional changes that increase the risk of injury and overuse. The authors emphasize the importance of maintaining individual symmetry during training and monitoring asymmetry. This approach may improve athletic performance and reduce injury risk.

Another study analyzed the relationship between asymmetry and athletic fitness [21]. Athletic asymmetry does not appear to have a clear impact on performance indicators. The weaker limb has greater potential for adaptation than the stronger limb and may demonstrate higher responsiveness to training.

The obtained data confirm this conclusion. The skill level of the participants ranged from beginners to elite athletes. However, it was not possible to establish differences in the severity of asymmetry depending on skill level.

KL athletes had a smaller range of motion in the right hand. Previous studies have confirmed that the right hand demonstrates higher strength indicators [33]. Increased strength is combined with reduced flexibility, which is consistent with the available literature and suggests greater effectiveness of the right hand in weightlifting.

Limitations of this study

The small sample size should be noted as a limitation of this study. This reduces the possibilities of statistical analysis and limits the ability to establish dependencies between indicators. The joint analysis of data from athletes with different skill levels also reduces the ability to identify the most important indicators for success.

The research quality can be improved by integrating goniometric indicators with morphological and psychophysiological parameters. This will allow for a comprehensive analysis of the morphofunctional status of kettlebell lifting and arm wrestling athletes.

Conclusions

Differences in the range of movements in the hand joints of kettlebell lifting and arm wrestling athletes have been established. Kettlebell lifting athletes had a greater range of movements in the wrist joints, the left elbow joint, the right shoulder joint (flexion, extension, and abduction), and the left shoulder joint (extension, abduction, and adduction). The flexion range of the right elbow joint was greater in arm wrestling athletes. These results illustrate the specific characteristics of kettlebell lifting and arm wrestling. Asymmetry was also significantly more pronounced in kettlebell lifting athletes. This reflects the specific demands of these sports. Goniometry is an objective, visual, and informative tool for assessing the condition of athletes. It can be used as a screening test for selecting and monitoring kettlebell lifting and arm wrestling athletes. The introduction of goniometric testing into practice may increase the effectiveness of athlete training.

Conflict of Interest

The authors declare no potential conflicts of interest.

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ORIGINAL ARTICLE

Relationship between technical–tactical indicators of attention and creativity and effort zones in youth football players during competitions

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

Abstract

Background and Study Aim Cognitive performance, specifically attention and creativity, contributes to the tactical effectiveness of youth football players. This contribution becomes evident when actions are executed under competitive physiological constraints. Examining how physical demands interact with perceptual and cognitive processes may support the development of training methodologies and competitive decision-making strategies. This study aims to analyze the relationship between technical–tactical indicators of attention and creativity and effort-zone parameters in young football players.

Material and Methods Twelve male football players (10–12 years old) from CSS1 Pajura Bucharest participated voluntarily in the study. Competition monitoring was conducted in 2022 and included 15 official matches in Series I and 14 matches in Series II. Functional parameters were assessed using Polar Vantage V devices. These parameters included heart rate (HR), running speed, total distance, and effort-zone distribution (Z1–Z5). Technical–tactical indicators of attention (CARR%) and creativity (ICV%) were quantified through video analysis. Descriptive statistics and Pearson correlation coefficients ($p < 0.05$) were calculated using KyPlot 6.0.

Results Competition effort showed a predominantly aerobic profile (Z1 + Z2 ≈ 53% by HR), interspersed with repeated short anaerobic episodes (Z3–Z5 ≈ 39%). Speed zones revealed mainly slow-to-moderate movements. This indicates that physiological intensity was largely generated by frequent game actions rather than locomotor velocity. Attention performance remained high and stable across matches (CARR 71.95–78.69%). Creativity values were consistently higher in Series II (ICV 7.69–9.09%). Correlation analysis revealed both positive and negative associations between cognitive and physical indicators. Moderate positive correlations were observed between attention and creativity indicators and moderate-intensity zones ($R = 0.30–0.46$). In contrast, high effort (HR-Z5) was associated with reduced cognitive efficiency ($R = −0.25$ to $−0.43$).

Conclusions The interaction between physiological load and cognitive–tactical performance should be considered when planning training and competition strategies for young football players. Attention to effort-zone regulation and its cognitive implications may assist coaches in structuring training tasks that account for both physical and cognitive demands. The combined assessment of physiological and technical–tactical indicators provides a framework for informed training design and decision-making support.

Keywords: youth football, cognitive performance, effort zones, attention, creativity

Introduction

In youth football, performance development is a key objective for coaches and researchers. This focus is related to the complexity of learning, development, and early specialization processes in young athletes. The development of technical–tactical competences and cognitive abilities, such as attention and creativity, is considered important during formative stages. These factors influence decision-making quality and the effectiveness of collective actions in football games

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[1]. The evaluation of tactical expertise through representative tasks has highlighted the relevance of integrating decision-making processes and creativity into the development of young football players. This approach supports the analysis of performance in realistic game environments [2]. In addition, previous studies indicate the need for a systematic development of tactical creativity from early ages to support cognitive flexibility and adaptation to the dynamic demands of football [3].

Recent research examines the interaction between technical–tactical demands and higher-order cognitive functions. Such functions, particularly attention and creativity, are involved in the assessment of competitive performance. The results of football games are not determined solely by physical training or technical skills. They are also influenced by players' ability to rapidly perceive game-specific information, make efficient decisions, and generate appropriate tactical solutions. Several studies have shown that perceptual–cognitive processes form the basis of tactical creativity and decision-making in sport. These processes include anticipation, selective attention, and working memory [4]. Cognitive models of decision-making suggest that athletes with greater attentional control can use environmental cues more effectively and select appropriate tactical actions [5]. In addition, individual differences in attentional capacity have been associated with creative decision-making processes. This supports an integrative view of cognitive mechanisms in the generation of tactical solutions during football play [6].

Attention, as a cognitive function in invasion sports, influences reaction speed, decision accuracy, and anticipatory behavior. These elements are involved in the execution of technical–tactical actions. In addition, in-game creativity is related to performance outcomes, particularly in youth football, where cognitive development and competitive experience are still developing. Creativity is defined by flexible solutions, original decisions, and the ability to select actions that are unexpected but effective [7, 8].

Another research direction concerns the analysis of effort zones during competition. This analysis provides objective data on the physiological intensity and physical demands experienced by players. In football, internal and external load indicators are routinely monitored. These indicators include speed, accelerations, distance covered in different intensity zones, and heart rate dynamics. This approach allows the examination of how players respond to the physical requirements of the game. Recent studies indicate the need to combine internal and external load metrics to obtain a valid assessment of training and competition load. These components may respond differently to competitive demands and may influence physiological adaptations and fatigue risk in distinct ways [9]. Modern tracking technologies, such as GPS systems and wearable devices, allow quantification of intensity zones and biomechanical and physiological demands during games. They support integrated performance analysis [10]. The association of these data with technical–tactical and cognitive indicators is increasingly addressed in research. This approach enables the examination of how young players manage physical, decisional, and tactical demands during competition [11].

A gap remains in research concerning the simultaneous examination of attention, creativity, and technical–tactical performance. These variables are not commonly analyzed in relation to effort-zone parameters during real competitive contexts in youth football. Most investigations address cognitive aspects or tactical effectiveness separately. They do not include physiological or external load indicators within the same analytical model. Previous studies have examined perceptual and cognitive processes related to decision-making and tactical performance in youth athletes [8, 12, 13]. In addition, research on tactical skill development indicates that experiential learning and exploratory behaviors are involved in performance. However, these aspects are rarely examined in relation to intensity-zone distribution under competitive conditions [14]. An integrated approach may allow the identification of multidimensional performance profiles and support training planning for young football players.

The aim of this study is to examine the relationships between technical–tactical indicators of attention and creativity and competition-related effort-zone parameters in young football players. The analysis focuses on identifying interaction patterns relevant to training processes and tactical strategies in youth football competitions.

Research hypotheses:

1. Relationships exist between attentional indicators (reaction performance and decision accuracy) and effort-zone parameters during competition. These relationships reflect the association between attentional control and the management of physical demands.
2. Technical–tactical creativity is associated with the intensity and distribution of effort zones. Creative actions are observed under varying load conditions.
3. Technical–tactical performance indicators are influenced by both attention and creativity. This suggests a multidimensional performance profile in competitive settings.

Materials and Methods

Participants

The study involved 12 football players aged 10–12 years from School Sports Club No. 1 Pajura, Bucharest. All participants and their parents were informed about the research procedures and provided voluntary consent. The study protocol was approved by the Ethics Committee of the Doctoral School of Sport Science and Physical Education, National University of Science and Technology "Politehnica Bucharest", University Center Pitești (ID: 19/18.10.2024).

Research Design

The research was conducted from September to December 2022 at School Sports Club No. 1 Pajura "Biruința" sports facility, Bucharest. The study was carried out in two stages (S): – S1 (22 October 2022): assessment of attention and creativity through video recording, together with functional monitoring using Polar heart rate devices during competition; – S2 (December 2022): analysis of an unofficial performance ranking from the first round of the Bucharest Municipal Championship for youth football players (2012 age group).

The total duration of the observation period was 15 weeks. This period included 15 matches in Series I and 14 matches in Series II of the competition. The general objective of the training program during the observation period was the strengthening and application of fundamental technical skills in directed game conditions (Table 1).

Assessment of functional indicators during competition

To monitor physiological and functional parameters during competitions, a Polar Vantage V sports watch was used. This high-precision device (Human Performance Research Center, University Center Pitești) is designed for performance evaluation in endurance sports. The system provided monitoring data on the following effort-related parameters:

– Monitoring duration (minutes);
– Total distance covered (km);
– Heart rate (HR): average (avg.), maximum (max.), minimum (min.);
– Running speed (km/h): average (avg.) and maximum (max.);
– Running pace (min/km): average (avg.) and maximum (slowest time per km);
– Cardio Load (%): an index expressing myocardial strain induced by exercise, based on a five-level scale: Very low (<20%); Low (20–39%); Medium (40–59%); High (60–79%); Very high (80–100%).

Effort zones used in the analysis

Monitoring was also performed per effort zones, both for heart rate (HR) and running velocity, based on the following classification:

Table 1. Thematic content of technical training – observational stage (Period: September – December 2022)

Week	Main technical theme	Specific objectives	Competition / testing observations
1-2	Ball control and dribbling with both feet	Directional control, changes of pace, use of both feet	Match E1: CSS1 vs. FCSB Match E2: Champion vs. CSS1
3	Basic dribbling and obstacle evasion	Controlled dribbling, simple feints	Match E3: CSS1 vs. Pro Luceafărul
4	Short passing (inside of the foot)	Accuracy, execution speed, synchronization with teammates	Match E4: Chelsea vs. CSS1
5	Oriented first touch (inside/ outside of the foot)	Ball redirection, efficient movements after reception	Match E5: CSS1 vs. Voinicelul
6-7	Finalization from movement	Proper striking technique using laces/inside, timing of the shooting	Match E6: Best Boys vs. CSS1 Match E7: CSS1 vs. CSA Steaua (1–1)
8	Long passing (laces/ exterior)	Ball transmission over long distances, precision and power	Match E8: CSU Știința vs. CSS1
9-10	Ball shielding	Body positioning, stability, game intelligence	Match E9: CSS1 vs. Lazio Celest Match E10: ACS Juniorul 2014 vs. CSS1
11-12	Combination plays 2 vs 1 / 3 vs 1	Cooperation, quick passing, rapid decision-making	Match E11: CSS1 vs. FC Rapid 1923 Match E12: New Stars vs. CSS1
13-14	Finishing with the head and volleying	Coordination, timing, confidence in aerial duels	Match E13: CSS1 vs. CS Dinamo Match E14: Progresul 1944 vs. CSS1
15	Review of technical skills and mini-competition	Enhancement and application of technical skills in game situations	CSS1 vs. FCSB Academy

– Heart rate zones (bpm): Z1: 100–120 bpm; Z2: 121–140 bpm; Z3: 141–160 bpm; Z4: 161–180 bpm; Z5: 181–200 bpm.
– Running speed zones (km/h): Z1: 3–6.9 km/h; Z2: 7–8.9 km/h; Z3: 9–10.9 km/h; Z4: 11–14.9 km/h; Z5: 15–19 km/h.

Both the percentage (%) and the absolute duration (minutes) spent within each intensity range were analyzed for each zone. Thus, an insight into the players' physiological adaptations and their ability to regulate effort under varying competitive demands was provided.

Technical–tactical tests for assessing attention and creativity indicators

The technical–tactical indicators of attention included:

- Simple passes (successful – R; unsuccessful – NR);
- Anticipation actions (number of executions);
- Loss of marking position (number of executions);
- Defensive duels initiated by the player (R and NR).

The technical–tactical indicators of creativity included:

- Complex passes (R and NR);
- Offensive duels initiated by the player (R and NR);
- Anticipation actions (number of executions).

To quantify the attention coefficient based on the results of successful and unsuccessful simple actions, a percentage ratio (%) was calculated. This reflected the efficiency and attentional focus of the players. In that regard, the Successful Action Rate (CA_{RR}) was applied as an objective measure of attention performance.

Attention coefficient based on the successful action rate (CA_{RR}%)

$$CA_{RR} = \frac{A_{\text{successful}}(R)}{A_{\text{successful}}(R) + A_{\text{unsuccessful}}} \times 100\%$$

where:

$A_{successful}$ = number of successful simple actions;

$A_{unsuccessful}$ = number of unsuccessful simple actions.

Interpretation:

- A higher coefficient highlights superior attentional control and more accurate execution of technical actions under competitive demands.
- A lower coefficient may reflect reduced attentional efficiency, difficulties in maintaining focus, or increased susceptibility to cognitive interference during play.

A calculation method was employed for quantifying the creativity indicator based on complex actions (complex passes, anticipatory movements, offensive duels). This method accounts for the intentionality, efficiency, diversity and difficulty of tactical executions. This approach relies on the video-based recording and coding of all complex and simple actions performed by the players. It aims not only to capture the frequency of executions but also their variability within the game context. In this way, the indicator reflects the players' ability to adapt, innovate and demonstrate decision-making flexibility under competitive constraints. Accordingly, the following calculation method is proposed:

Decision variability creativity index (ICV%):

$$IC_V = \frac{A_{\text{individual}}}{A_{\text{group}}} \times 100\%$$

where:

$A_{individual}$ – total number of individual complex actions;

A_{group} – total number of complex actions performed by the group.

Interpretation: A player who uses a wide range of tactical solutions to respond to diverse game situations has a higher ICV value. This indicates an enhanced creative performance.

Statistical analysis

Statistical analysis was performed using KyPlot 6.0. Descriptive statistics included mean, standard error of mean (SEM), standard deviation (SD), coefficient of variation (CV%) and Confidence level of mean (0.95) (CLM0.95). The relations between indicators of attentional and creative involvement in technical–tactical actions and the physiological monitoring parameters were examined. This analysis was performed by calculating the Pearson's correlation coefficients. Statistical significance was established at $p < 0.05$.

Results

An analysis of attentional and creativity indicators related to physiological effort parameters and effort-zone distribution in 10–12-year-old footballers was conducted. The data were collected under competitive conditions. The results are presented in Tables 2–5 and Figures 1–3. These include the evolution of values across consecutive matches. They also include the correlation relationships between physical demands and cognitive performance in a real competitive context.

Table 2 summarizes the comparative results between Competitive Series I and II of the 2022–2023 Municipal Championship (second half). Football players aged 10–12 were monitored in terms of attentional and creative performance across five official matches (M1–M5). The evaluation involved two key indices: Attention Coefficient (CARR %) and Creativity Variability Index (ICV %), both expressed as percentages.

Analyzing the technical–tactical indicators of attention (CARR%) and creativity (ICV%) reveals

Table 2. Comparative results of the technical–tactical indicators of attention and creativity in competition

Descriptive statistical indicators	Series of competition	CA_{RR} (%)					IC_V (%)				
		M1	M2	M3	M4	M5	M1	M2	M3	M4	M5
Mean	I	71.95	78.69	72.82	72.96	75.85	6.67	6.67	7.69	7.69	7.69
	II	74.59	76.71	70.32	73.07	77.17	8.33	7.69	8.80	9.09	8.33
SEM	I	4.29	4.05	2.89	4.26	3.03	0.85	0.88	1.11	1.04	0.68
	II	3.08	3.54	5.61	4.60	3.05	0.92	1.28	1.79	1.14	0.98
SD	I	16.62	15.67	10.43	15.35	10.91	3.28	3.40	4.01	3.75	2.44
	II	10.67	12.75	18.61	15.26	10.57	3.19	4.60	5.95	3.76	3.40
CV (%)	I	23.10	19.92	14.32	21.0	14.39	49.17	50.98	52.15	48.76	31.77
	II	14.31	16.62	26.46	20.88	13.70	38.33	59.77	67.68	41.41	40.86
CLM (0.95)	I	9.21	8.68	6.30	9.27	6.59	1.82	1.88	2.42	2.27	1.48
	II	6.78	7.70	12.50	10.25	6.72	2.03	2.78	4.00	2.53	2.16

Notes: Th-Ta – technical-tactical, CARR – coefficient of attention – success rate; ICV –creativity indicator – variation of decisions; M – match; Confidence level of mean (0.95) – CLM (0.95); Series I: M1 and M2, n=15, M3-5, n=13; Series II: M3 and 4, n=11; M1 and M5, n=12, M2, n=13

Table 3. Results of competitive effort parameters in Series I

Effort parameters		Descriptive statistical indicators				
		mean	SEM	SD	CV (%)	CLM(0.95)
Effort duration monitoring (min)		69.54	0.86	2.97	4.27	1.88
Total distance covered (km)		2.19	0.07	0.25	11.56	0.16
HR (bpm)	Avg.	136.58	2.95	10.23	7.49	6.50
	Max	190.83	3.44	11.92	6.25	7.58
	Min	68.00	4.02	13.92	20.46	8.84
Speed (km/h)	Avg.	1.83	0.07	0.23	12.39	0.14
	Max	18.55	0.71	2.48	13.35	1.57
Pace (min/km)	Avg.	32.02	1.23	4.27	13.34	2.71
	Max	3.10	0.14	0.49	15.68	0.31
Cardio load (%)		90.33	8.12	28.11	31.12	17.86

Note: n=12, Heart rate (HR; bpm), Confidence level of mean (0.95) – CLM (0.95)

Table 4. Proportion of time spent in effort zones based on heart rate (HR) and running speed (V) during competitive play in Series I

Parameters / effort zones		mean	SEM	SD	CV (%)	CLM (0.95)
HR (bpm, %)	Z5	10.17	2.84	9.83	96.72	6.25
	Z4	12.83	2.36	8.17	63.64	5.19
	Z3	15.67	1.58	5.48	35.00	3.48
	Z2	30.00	3.00	14.88	49.60	9.46
	Z1	22.58	2.50	8.65	38.30	5.50
Speed (km/h, %)	Z5	0.00	0.00	0.00	0.00	0.00
	Z4	0.58	0.15	0.51	88.27	0.33
	Z3	1.83	0.30	1.03	56.17	0.65
	Z2	7.42	0.62	2.15	29.01	1.37
	Z1	25.33	0.77	2.67	10.56	1.70

Note. Z – zones of effort

Table 5. Duration of effort zones during competition based on heart rate and speed (Series I)

Parameters / effort zones		mean	SEM	SD	CV (%)	CLM (0.95)
HR (bpm, min)	Z5	6.90	2.01	6.98	101.20	4.43
	Z4	8.68	1.55	5.37	61.90	3.41
	Z3	10.84	1.16	4.01	36.95	2.54
	Z2	20.89	3.09	10.72	51.31	6.81
	Z1	15.57	1.69	5.85	37.57	3.72
Speed (km/h, min)	Z5	0.02	0.01	0.02	118.17	0.01
	Z4	0.19	0.04	0.13	68.00	0.08
	Z3	1.10	0.20	0.70	63.88	0.45
	Z2	4.90	0.45	1.55	31.64	0.98
	Z1	17.37	0.45	1.57	9.03	1.00

Note. Z – zones of effort

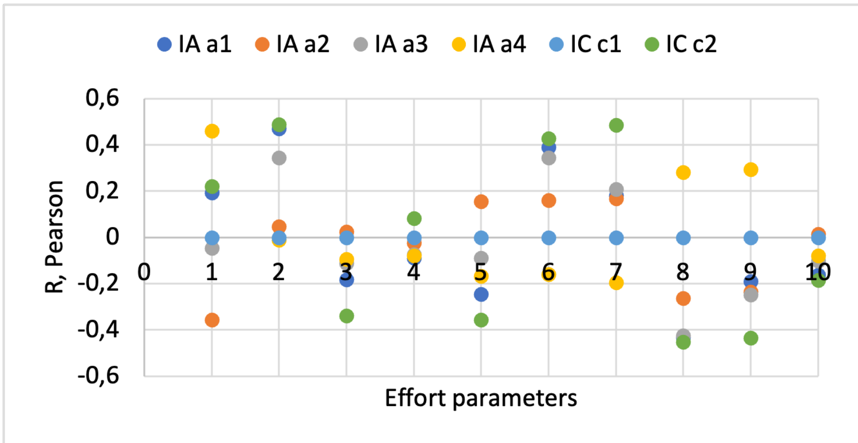

Figure 1. Analysis of correlations between attention and creativity indicators and competitive effort parameters (Series I). Notes: Effort parameters (1–10): 1 – effort monitoring duration; 2 – total distance; 3–5 – HR (bpm): avg., max., min.; 6–7 – speed (km/h): avg., max.; 8–9 – pace (min/km): avg., max.; 10 – cardio load (%). IA – indicators of attention (a1–a4): a1 – successful simple actions; a2 – unsuccessful simple actions; a3 – total simple actions; a4 – CARR (%) – coefficient of attention. IC – indicators of creativity: c1 – total complex actions; c2 – ICV (%).

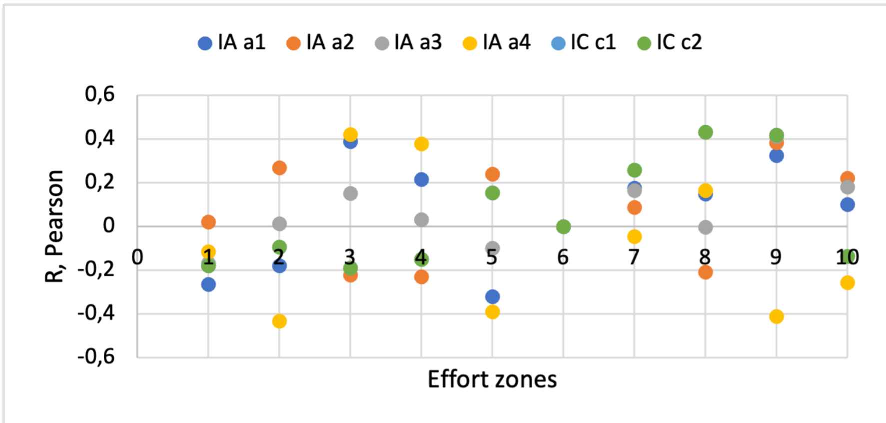

Figure 2. Correlations between attention and creativity indicators and the proportion of effort zones during competition (Series I). Notes: IA – indicators of attention (a1–a4): a1 – successful simple actions; a2 – unsuccessful simple actions; a3 – total simple actions; a4 – CARR (%) – coefficient of attention. IC – indicators of creativity: c1 – total complex actions; c2 – ICV (%). HR zones: 1 – Z5; 2 – Z4; 3 – Z3; 4 – Z2; 5 – Z1. Movement speed zones: 6 – Z5; 7 – Z4; 8 – Z3; 9 – Z2; 10 – Z1.

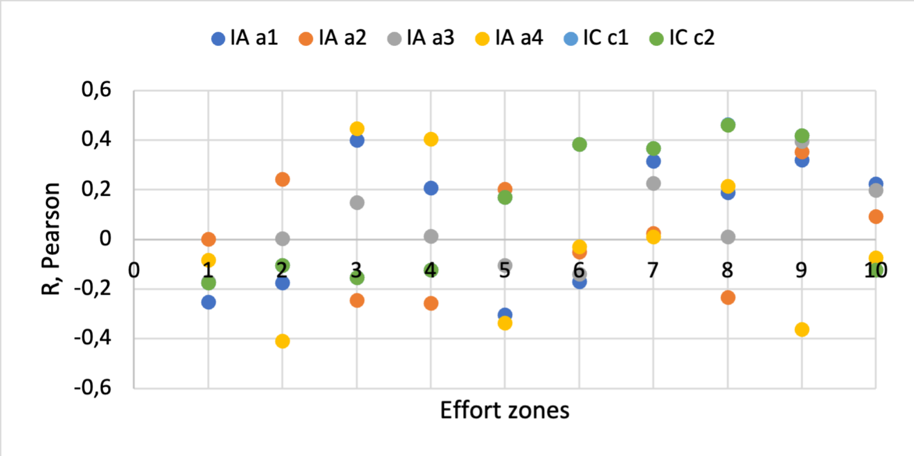

Figure 3. Correlations between attention and creativity indicators and the duration of effort zones during competition (Series I). Note. IA – indicators of attention (a1–a4): a1 – successful simple actions; a2 – unsuccessful simple actions; a3 – total simple actions; a4 – CARR (%) – coefficient of attention. IC – indicators of creativity: c1 – total complex actions; c2 – ICV (%). HR zones: 1 – Z5; 2 – Z4; 3 – Z3; 4 – Z2; 5 – Z1. Movement speed zones: 6 – Z5; 7 – Z4; 8 – Z3; 9 – Z2; 10 – Z1.

differences between the two series across the competitive sequence (M1–M5). Regarding the attention coefficient (CARR%), both series showed high and relatively stable values. Mean values ranged between 71.95% and 78.69% in Series I and between 70.32% and 77.17% in Series II. Series I reached a peak in M2, followed by a moderate decline. In contrast, Series II showed a slight increasing trend, indicating progressive adaptation to competitive demands.

In contrast, the creativity indicator (ICV%) showed clearer differences between the two series. Series I increased gradually from 6.67% (M1–M2) to 7.69% (M3–M5), whereas Series II consistently showed higher values. Series II values ranged from 7.69% to 9.09%, reflecting greater decision-making flexibility and tactical variability.

Variability analysis (SEM, SD, CV%) indicated greater dispersion of creative performance in Series II, particularly in M3 (CV = 67.68%). This suggests pronounced individual differences in the expression of creativity under competitive conditions.

Table 3 provides an overview of the intensity and efficiency of physical effort exerted by 10–12-year-old football players. Data were collected during Match 4 of the first competitive round of the 2022–2023 Championship. For this purpose, heart rate (HR), locomotor speed, running pace, and cardiovascular load ("Cardio Load") were monitored.

The analysis of the physiological parameters monitored during competition indicates a medium-to-high intensity effort profile. This profile is characterized by alternations between maximal exertion episodes and phases of active recovery. The average duration of effort was 69.54 minutes, with low variability (CV = 4.27%), reflecting a consistent level of competitive engagement. The average total distance covered was 2.19 km, suggesting moderate involvement in high-intensity locomotor actions.

Cardiovascular parameters indicate a substantial demand on the cardiorespiratory system. The mean heart rate was 136.58 bpm, the peak value was 190.83 bpm, and the cardio load level was high (90.33%). The variability observed in minimum heart rate and cardiovascular load (CV ⩾ 20%) indicates individual differences in effort regulation capacity. The average running speed was low (1.83 km/h), which is consistent with the intermittent nature of football at this age. Peak speed (18.55 km/h) indicates the occurrence of high-acceleration actions during specific phases of the game.

Overall, the effort profile reflects a mixed aerobic–anaerobic model determined by the rapid alternation of game phases. These data provide a physiological basis for interpreting the interplay between physical demands and cognitive performance (attention and creativity). This interaction is further examined in the following sections.

Table 4 presents the percentage distribution of time spent by 10–12-year-old football players in different effort zones. The results are based on both heart rate (HR) and running speed (V) during competitive games. Analysis of these data allows the examination of relative intensity of physical exertion and physiological engagement strategies throughout the competition.

Results on effort distribution across physiological zones (Series I)

The percentage distribution of effort reflects a predominantly aerobic competitive profile with distinct episodes of high-intensity activity. Based on heart rate (HR) data, athletes spent the largest proportion of time in Zone 2 (30.00%). A smaller proportion was observed in Zone 1 (22.58%). This indicates a predominance of moderate effort and active recovery (cumulative 52.58%). In addition, 38.67% of the competition duration occurred in higher-intensity zones (Z3–Z5). This confirms the involvement of anaerobic mechanisms during tactical situations requiring high effort.

From the perspective of movement speed, effort was concentrated almost exclusively in low-speed zones (Z1–Z2 = 32.75%). Zones 3–5 recorded minimal values, with maximal sprints absent (Z5 = 0%). This discrepancy suggests that physiological intensity was determined more by the frequency and nature of game actions than by locomotor speed. High variability was observed in maximal intensity zones (CV > 60% in Z4–Z5). This indicates marked individual differences in effort profiles and tactical roles of the players.

The data demonstrate a mixed aerobic–anaerobic effort pattern characteristic of youth football. This pattern includes intermittent sequences of maximal-intensity activity combined with periods of moderate activity. These data provide a basis for further correlation with attention and creativity indicators to examine competitive performance.

Table 5 presents the temporal distribution of effort during competition. The table is based on the time (in minutes) spent in each intensity zone according to both heart rate and running speed. These data describe the physical characteristics of effort and reflect the predominance of specific physiological activity regimes.

Results on the duration of effort zones during competition (Series I)

Analyzing the effort duration across physiological zones confirms the predominance of an aerobic regime. Players spent most of the time in Zone 2 (20.89 min) and Zone 1 (15.57 min). This indicates a moderate activity pace with frequent periods of active recovery. High-intensity episodes also contributed to the competitive profile. Zones 3–5 accounted for a total of 26.42 minutes, including approximately 7 minutes in Zone 5. This indicates the presence of anaerobic demands during decisive phases of the game.

Regarding movement speed, time was mainly spent in low-speed zones (Z1–Z2), with only occasional engagement in faster actions. Zones 3–5 together accounted for less than 8% of the total duration, and maximal sprints were almost absent (Z5 = 0.02 min). High variability in these zones (CV > 60%) indicates individual differences in tactical roles and fitness levels. A contrast was observed between high cardiovascular demand and low average speed. This suggests that competitive intensity is generated by the frequency and nature of game actions rather than by fast movement alone. The resulting profile reflects a mixed aerobic–anaerobic pattern of effort characteristic of youth football. This allows correlations with indicators of attention and creativity.

The influence of technical–tactical indicators of attention and creativity on effort parameters and effort zones during competition was examined. For this purpose, linear correlation analysis (Pearson's R) was conducted.

Figures 1–3 present the statistical relationships between attention and creativity indicators and selected effort parameters during competition (Series I). These figures illustrate the association between cognitive processes and overall effort intensity, as well as effort distribution and duration across physiological stress zones.

Figure 1 presents the Pearson correlation matrix between cognitive variables (attention and creativity) and physiological effort parameters. A total of 60 correlations were analyzed, of which 26 (43.3%) were positive and 34 (56.7%) were negative. These values indicate a general tendency toward inverse associations between physical exertion intensity and cognitive performance.

Positive correlations were mainly observed between attention and creativity indicators and selected effort parameters. This suggests that moderate-to-high levels of physiological activation may be associated with attentional engagement in competitive situations. Examples include total duration (2) and successful simple actions (a1) ($r = 0.472$), indicating a moderate association between effort involvement and attentional processes. Average speed (km/h, Avg., 6) showed a positive association with a1 ($R = 0.391$), while maximum speed (km/h, Max., 7) was weakly associated with unsuccessful simple actions (a2) ($R = 0.169$). In addition, effort monitoring duration (1) and parameter (7) showed moderate positive correlations with creativity indicators c1 (total complex actions) and c2 (ICV %) ($R = 0.48–0.49$), suggesting increased cognitive engagement during demanding phases of play.

Most negative correlations were observed between movement speed parameters (pace, min/km: Avg. (8) and Max (9)) or maximal intensity indicators and sustained attention indicators (a1), average heart rate (HR Avg., 3), and minimum heart rate (HR Min., 5). Representative examples include correlations between parameter 8 and a1 ($R = -0.431$) and between pace Max (9) and a2 ($R = -0.236$). These moderate associations suggest a possible inhibitory effect of higher effort intensity on attentional accuracy. A moderate negative correlation was also observed between parameter 5 and c1 ($R = -0.357$), indicating reduced creative expression under higher load conditions. In addition, correlations between parameter 3 and cardiovascular indicators ($R = -0.11$ to -0.18) were weak but consistent, suggesting gradual cognitive fatigue.

The predominance of negative correlations indicates that high-intensity (anaerobic) episodes may interfere with executive functions. Such interference may affect reaction speed, cognitive flexibility, and creative processes. No correlation exceeded the threshold of R ⩾ 0.50, indicating a complex and multifactorial relationship between physiological effort and cognitive functions at this age.

Figure 2 illustrates the Pearson correlations between attention (AI), creativity (CI) parameters and the proportion of time spent in different effort zones defined by heart rate (HR) and movement speed (V). A total of 60 correlations were analyzed. Of these, 27 (45%) were positive, while 33 (55%) were negative. This indicates a predominantly inverse relationship between high physical exertion and cognitive performance.

Positive correlations were more frequently associated with moderate-intensity zones (V-Z2–Z4) and intermediate cardiac effort zones (HR-Z3–Z4). This indicates an association between physiological activation and vigilance and creativity. Representative examples include correlations between Z3 and a1 (r = 0.389) and between Z3 and a4 (r = 0.420), which indicate that cardiovascular activation is associated with attentional processes during tactically demanding moments. Positive associations were also observed between Z2 and a1 (R = 0.215) and between Z2 and a4 (R = 0.378), reflecting relationships between effort and distributive attention. Creativity indicators (c1–c2) showed moderate positive correlations with average speed zones, including Z3 with c1/c2 (R = 0.432) and Z2 with c1/c2 (R = 0.418). These associations indicate that creative actions tend to occur during short accelerations and dynamic game situations. These patterns are consistent with the optimal arousal framework, which describes improved cognitive performance at moderate levels of effort intensity.

Negative correlations were predominantly observed in extreme physiological zones (HR-Z1 and HR-Z5) and sustained attention indicators, reflecting interference associated with overload. Representative examples include Z2 with a4 (R = −0.432), indicating reduced selective attention at high cardiac intensity, and Z1 with a1 (R = −0.320) and Z1 with a4 (R = −0.389), indicating reduced attentional control under maximal effort. Zone 5 showed weak negative correlations across cognitive–tactical parameters (R = −0.11 to −0.26), suggesting cognitive fatigue during periods of high-intensity play. For movement speed, the correlation between Z2 and a4 (R = −0.411) indicates that involvement in explosive actions is associated with reduced decision-making control.

The predominance of negative correlations indicates that repeated anaerobic effort may adversely affect cognitive flexibility, reaction time, and decision-making creativity.

Figure 3 presents Pearson correlations between attention (AI) and creativity (CI) indicators and the time spent by athletes in different physiological effort zones. These zones are defined by heart rate (HR: Z1–Z5) and movement speed (V: Z1–Z5). A total of 60 correlations were analyzed, of which 29 (48.3%) were positive and 31 (51.7%) were negative. This reflects a balance between associations indicating facilitation and interference of physical load with cognitive functions.

Positive correlations were mainly observed in moderate effort zones. For heart rate, correlations were found between Z3 and a1 (R = 0.401) and between Z3 and a4 (R = 0.448). These moderate associations indicate that longer durations at upper-aerobic intensity are associated with attention during dynamic tactical situations. A positive correlation was also observed between Z2 and a4 (R = 0.404), indicating an association between sustained submaximal effort and attentional control.

For movement speed, correlations were identified between Z2 and a1 (R = 0.321) and between Z2 and a3 (R = 0.395). These results indicate that short-duration accelerations are associated with vigilance and reaction processes. Moderate effort durations, particularly in zones Z3–Z4, are associated with levels of physiological activation related to selective attention and information processing (Th–Ta).

Positive correlations associated with durations in speed zones were more numerous and consistent: Z3–c1/c2 (R = 0.463), which was the highest positive correlation in the series; Z2–c1/c2 (R = 0.418); Z5–c1/c2 (R = 0.383); and Z4–c1/c2 (R = 0.367). Short periods of medium- or high-speed movement are associated with the generation of varied technical–tactical solutions, reflecting operative creativity during play.

Comparative analysis of the results shows concordance in the distribution of correlations between Th–Ta parameters (attention and creativity) and physical effort indicators. These are expressed through effort parameters, the proportion of time spent in different physiological zones, and the duration within these zones.

Discussion

The study results indicate specific relationships between cognitive technical–tactical performance (attention and creativity) and physiological demands during competition in football players aged 10–12 years. The convergence of comparative and correlation analyses reflects the mixed nature of competitive effort and its association with cognitive mechanisms involved in decision-making.

Repeated exposure to competitive situations is associated with changes in decision-making processes and cognitive flexibility. This assumption is supported by the upward trend observed in sustained attention (CARR%) and the differentiation of decision-making creativity (ICV%) in Series II.

These observations are consistent with previous research showing that tactical experience and repeated engagement in unpredictable contexts reduce cognitive load during decision-making [15, 16]. Such conditions are also associated with the expression of technical–tactical creativity in young athletes [4, 17, 18].

Analyzing effort zones reveals a predominantly aerobic profile, interspersed with short bouts of high intensity, reflecting the intermittent nature of youth football. Accordingly, the hypothesis that physical demand is not solely dependent on locomotion speed but also influenced by neuromuscular, decisional, and emotional factors is supported. This observation is consistent with studies indicating the role of aerobic endurance in the development of tactical performance in young football players [19, 20].

Correlation analysis showed a substantial proportion of negative relationships (52–57%). These associations indicate that high physiological demands may interfere with attentional control and tactical creativity. This pattern corresponds to the inverted-U model describing the relationship between effort and cognition [21], according to which cognitive performance is highest at moderate activation levels and decreases under lower or excessive activation. In contrast, moderate positive correlations (R = 0.30–0.46) indicate an association between dynamic engagement and decision-making processes and tactical–creative flexibility in young players. These correlations were related to upper-aerobic zones (HR-Z2–Z3) and medium movement speeds [19, 22, 23].

The present findings expand previous football research by indicating that physiological load alone does not fully explain performance variability in young players. Studies focusing on body composition and biomotor parameters [24] as well as on player load and anaerobic performance [25] emphasize physical determinants of performance. In contrast, the current results suggest that high or prolonged intensity may interfere with attentional stability and creative decision-making, whereas moderate-intensity effort appears more favorable for optimal cognitive–tactical functioning. This perspective supports a more integrated interpretation of performance regulation under competitive conditions.

The findings of this study confirm the need for optimal synchronization of physical demand intensity and cognitive requirements when designing tasks for young footballers. Alternating moderate-effort sequences with highly unpredictable tactical situations can enhance both physical and decision-making performance [8, 26, 27, 28]. Objective monitoring using physiological parameters such as heart rate and internal load enables the individualized and real-time optimization of competitive regulation [29].

Overall, the present study adds to the existing literature by demonstrating the interdependence between physiological load and cognitive–tactical performance in football. The findings indicate that the regulation of effort intensity is relevant not only for physical efficiency but also for attentional control and creative decision-making under competitive conditions. From a practical perspective, the results support the consideration of combined physiological and cognitive demands when structuring training tasks and competitive preparation. Such an approach may assist in aligning physical load management with the development of tactical and decisional performance.

Limitations of the Study and Future Research

This study has several limitations that should be considered when interpreting the findings. The relatively small sample size and the focus on a single age group may limit the generalizability of the results to other competitive levels or age categories. In addition, the observational design restricts causal inference between physiological load and cognitive–tactical performance. Future research should include larger and more diverse samples, longitudinal designs, and experimental task manipulations to further clarify the interaction between physical demands, attentional processes, and creative decision-making in football.

Conclusions

1. The competitive effort profile in 10–12-year-old players is predominantly aerobic, with short episodes of maximal intensity. This profile reflects physiological characteristics of youth football and provides conditions for functional adaptation.
2. Moderate-intensity effort is positively associated with attention and creativity. This association indicates that psychophysiological activation at moderate levels is related to decision-making processes and tactical flexibility during play.
3. Maximal intensity or prolonged exertion is associated with interference in information processing and creativity. This reflects limitations of cognitive control when physiological load exceeds self-regulation capacity in young athletes.
4. Competitive experience is associated with greater stability of cognitive functions. Repeated exposure to real-game situations is accompanied by more consistent levels of selective attention and tactical–decisional creativity.
5. Joint analysis of physiological, attentional, and creative indicators supports the use of a multidimensional approach to evaluating youth performance. This approach allows the consideration of individual cognitive–physiological profiles in training design.

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Conflict of interest

The authors declare no conflict of interest.

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