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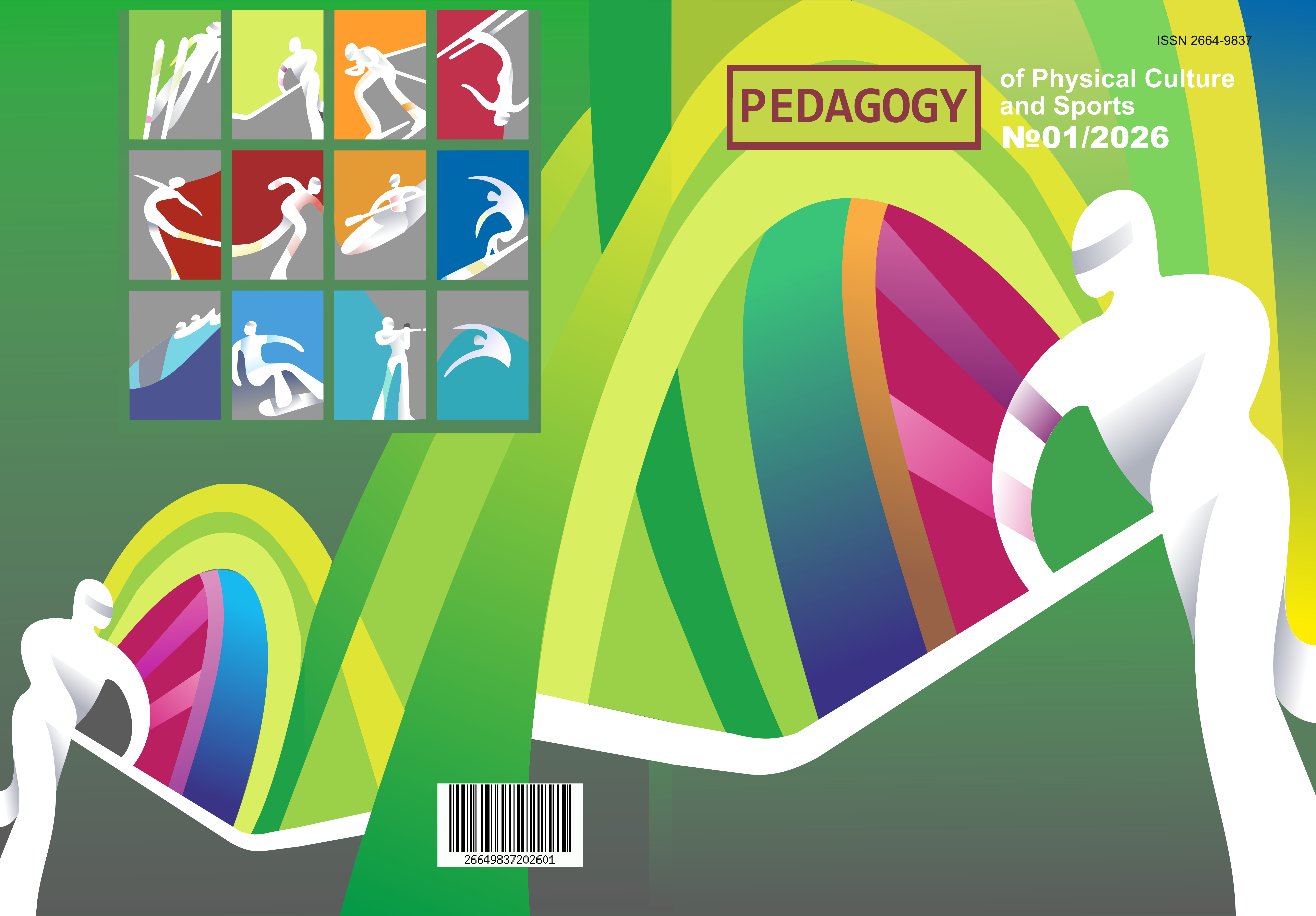

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ORIGINAL ARTICLE

Effects of accentuated eccentric loading on explosive strength and agility in basketball 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 Basketball performance depends on the development of physical qualities that support fast and efficient movement. Explosive strength and agility contribute to rapid acceleration, jumping, and changes in direction during gameplay. Despite the use of various training methods, their relative effectiveness in improving these qualities remains a subject of practical interest. This study aimed to determine the effectiveness of Accentuated Eccentric Loading training in enhancing explosive strength and agility among collegiate basketball players.

Material and Methods Thirty-two state-level male collegiate basketball players (age 18–25 years) were assigned into experimental and control conditions representing both rural and urban training environments. The experimental groups completed a six-week Accentuated Eccentric Loading program performed three times weekly, with eccentric overload initialized at 30% of body mass and progressively increased across sessions. Control groups continued regular basketball practice without additional eccentric loading. Explosive strength was assessed using the Vertical Jump Test, while agility was measured through the Agility T-Test. Performance was evaluated pre- and post-intervention. Data analysis included paired t-tests to examine within-group change and ANCOVA to compare post-intervention outcomes between groups while controlling for baseline values.

Results Accentuated Eccentric Loading led to measurable improvements in explosive strength and agility ($p < 0.05$). AEL groups demonstrated greater progress than controls, indicating that eccentric loading produced a stronger training effect than regular practice. Post-hoc comparisons showed a consistent advantage of AEL in both rural and urban subgroups. This suggests that the effectiveness of the method was similar across different training environments. Overall, AEL improved jump performance and directional movement capacity within a six-week training cycle.

Conclusions The findings indicate that AEL training is effective in improving explosive strength and agility in collegiate basketball players. The results support its practical application for coaches and trainers aiming to enhance performance in competitive basketball.

Keywords: explosive strength, agility, accentuated eccentric loading, eccentric phase, vertical jump

Introduction

Basketball performance is shaped by physical, technical, and tactical demands that require athletes to sustain dynamic activity throughout gameplay. Explosive strength and agility influence acceleration, vertical force production, and rapid directional transitions during offensive and defensive actions. These qualities interact within a high-speed environment, where any delay or loss of power may affect the outcome of an episode and the overall course of the game. For athletes, speed and explosive strength are essential qualities that form the basis of success in sports requiring quick reflexes and high-energy bursts. These characteristics are important in sports where rapid direction changes, quick acceleration, and controlled deceleration are required. In games like basketball, explosive strength and agility play a central role [1, 2].

In muscular contraction, two phases are observed: concentric and eccentric, referring to muscle shortening and lengthening, respectively [3]. Physiological study of eccentric muscle work has a long research tradition. The concept of eccentric muscle action as distinct from concentric work is well established in the literature [4]. Eccentric or negative resistance training focuses on the lengthening phase of contraction. In strength and conditioning programs, eccentric exercises are applied to load muscles in the opposite direction of the pull using external resistance [5]. It has long been recognized that skeletal muscles generate greater force during eccentric activity compared with concentric movements [6]. Eccentric loading can overload the

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muscular system with comparatively low energy expenditure [7]. Therefore, eccentric training is considered a meaningful component of strength and conditioning programs aimed at improving performance or reducing injury risk in sport [4].

An approach used to improve physical characteristics in athletes is Accentuated Eccentric Loading (AEL), a training method focused on the lengthening phase of movement. AEL is considered an extension of eccentric exercise concepts. It involves applying a greater load during the eccentric phase compared with the concentric phase of a coupled eccentric–concentric action [8, 9]. Earlier work suggests that increasing external load in the eccentric phase of a jump may influence the stretch-shortening mechanism and affect jump execution and performance [10]. By emphasizing muscle lengthening under resistance, AEL may promote changes in neuromuscular function and muscle performance [11]. This has contributed to its growing use among coaches and conditioning professionals seeking to enhance training outcomes.

Explosive strength refers to the short-term ability to generate maximal muscle force and accelerate movement of the whole body or its segments. Explosive muscle force may be described as the capacity to overcome external resistance within a rapid force-producing action [12, 13]. This quality reflects the quick development of force through fast muscular contraction during actions that require high output over a brief time. Sports requiring high loading and rapid force transfer through the lower limbs include skiing, weightlifting, diving, and team sports such as basketball, football, and volleyball [13].

Agility may be described as a rapid whole-body action that involves changes in velocity or movement direction in response to an external stimulus. It integrates trainable physical qualities such as strength, power, and technical execution with cognitive processes including anticipation, decision-making, and visual scanning strategies. In practice, assessment of agility often focuses either on physical components, such as change-of-direction speed, or on cognitive elements such as anticipation and pattern recognition [14, 15]. Agility development has been associated with improvements in movement efficiency, balance control, and reactive decision-making during high-intensity sport situations [16]. This movement quality is relevant across a broad spectrum of sports, including individual disciplines such as tennis and combat sports, and team games such as basketball [17].

Given the role of agility and explosive movement capabilities in performance, regional evidence is relevant when considering how training responses may differ across athletic environments. Research involving athletes from South Asia reports the use of structured strength-oriented preparation at competitive and university levels. Comparative findings in cricket, football, and volleyball indicate differences in strength, explosive power, speed, endurance, and agility between rural and urban athlete groups, with several studies noting higher test outcomes among rural participants in pull-ups, abdominal strength, shuttle runs, and standing broad jumps [18, 19, 20, 21]. Experimental work also shows that interval-based, resistance-based, and core-strength interventions can improve neuromuscular output, anaerobic performance, movement speed, and body-composition parameters in regional sport contexts [22, 23, 24].

These observations suggest that strength-development strategies are already applied within South Asian athletic populations and can lead to measurable adaptation. However, most of this evidence relates to general resistance training, whereas methods involving accentuated eccentric work have been examined less frequently in relation to agility and explosive force expression in basketball. This indicates the value of evaluating eccentric-focused training models in environments that differ in equipment access, coaching provision, and training load.

Research comparing rural and urban athletes under eccentric-based interventions remains limited, even though training infrastructure and resource availability can differ considerably. Comparable performance responses to Accentuated Eccentric Loading (AEL) under varying training conditions may indicate how preparation models can be adapted for different collegiate settings.

It was hypothesized that explosive strength and agility would increase following AEL intervention, without large differences between rural and urban training environments. This study aimed to determine the effectiveness of Accentuated Eccentric Loading training in enhancing explosive strength and agility among collegiate basketball players.

Materials and Methods

Participants

The study involved 32 state-level male collegiate basketball players aged 18–25 years, all actively engaged in competitive play. Participants were selected using a non-probability convenience sampling procedure and represented both urban (n = 16) and rural (n = 16) training environments. They were allocated to four groups: Urban Control (UCON), Urban Accentuated Eccentric Loading (UAEL), Rural Control (RCON), and Rural Accentuated Eccentric Loading (RAEL). Athletes from different on-court positions, including guards, forwards, and centers, were included to represent varied performance characteristics.

A priori sample estimation was performed using G*Power 3.1 to determine the minimum number required to detect a training effect. The calculation was based on an F-test for group comparison with covariate adjustment (ANCOVA, fixed effects), with $\alpha = 0.05$, statistical power $(1 - \beta) = 0.80$, four groups, and one covariate. An effect size of $f = 0.35$ was selected from prior eccentric-loaded and plyometric research. The estimated minimum sample was 28 participants; 32 players were recruited to allow for dropouts and to maintain equal group size.

All athletes received study information and provided written informed consent prior to participation. Ethical approval was granted by the Institutional Human Ethics Committee, and study procedures followed the principles of the Declaration of Helsinki [25].

Study Design

The research employed a quasi-experimental design within a quantitative framework using non-probability convenience sampling. Accentuated Eccentric Loading (AEL) was the intervention condition, whereas explosive strength and agility served as outcome variables. Participants allocated to the UAEL and RAEL groups completed a six-week AEL program delivered three times per week on alternate days, with eccentric overload set at 30–35% of body mass via weight releasers or external loading during the eccentric phase. Each session included a standardized warm-up, progressive plyometric drills, and eccentric-emphasis jump variations. The control groups (UCON and RCON) continued regular basketball training that involved warm-up routines, technical-tactical practice, scrimmage play, and basic strength work without eccentric overload. Plyometric exercises with added resistance were not incorporated into control training.

Pre-intervention testing was conducted before the program commenced, and post-testing followed completion of Week 6. A visual outline of participant flow, subgroup allocation, and final sample retention is presented in Figure 1.

Weekly Progressive AEL Training Protocol

Training sessions were held three times per week on alternate days for six consecutive weeks. Performance testing included the Vertical Jump Test and the Agility T-Test before the intervention and repeated at the end of Week 6. The AEL protocol was developed with reference to previously documented methods [3, 26]. Eccentric loading was applied using weight releasers during back-squat movements and weighted vests (5–12 kg) for drop-jump and broad-jump variations. All eccentric repetitions were executed with a controlled lowering phase of approximately 3 seconds, followed by an explosive concentric action. Tempo monitoring was maintained through verbal cues and metronome pacing when required. All sessions were supervised by two certified strength and conditioning professionals with at least five years of applied training experience.

A weekly breakdown of training progression is summarized in Table 1, and the load progression across six weeks is shown graphically in Figure 2.

Outcome Measurements

All performance assessments were conducted under standardized conditions. Each testing session was preceded by a warm-up that included 5 minutes of jogging, dynamic stretching, and submaximal jump attempts. Testing was scheduled at the same time of day (±1 hour) to reduce diurnal variation. Assessors conducting the vertical jump and agility tests were blinded to group allocation. Inter-

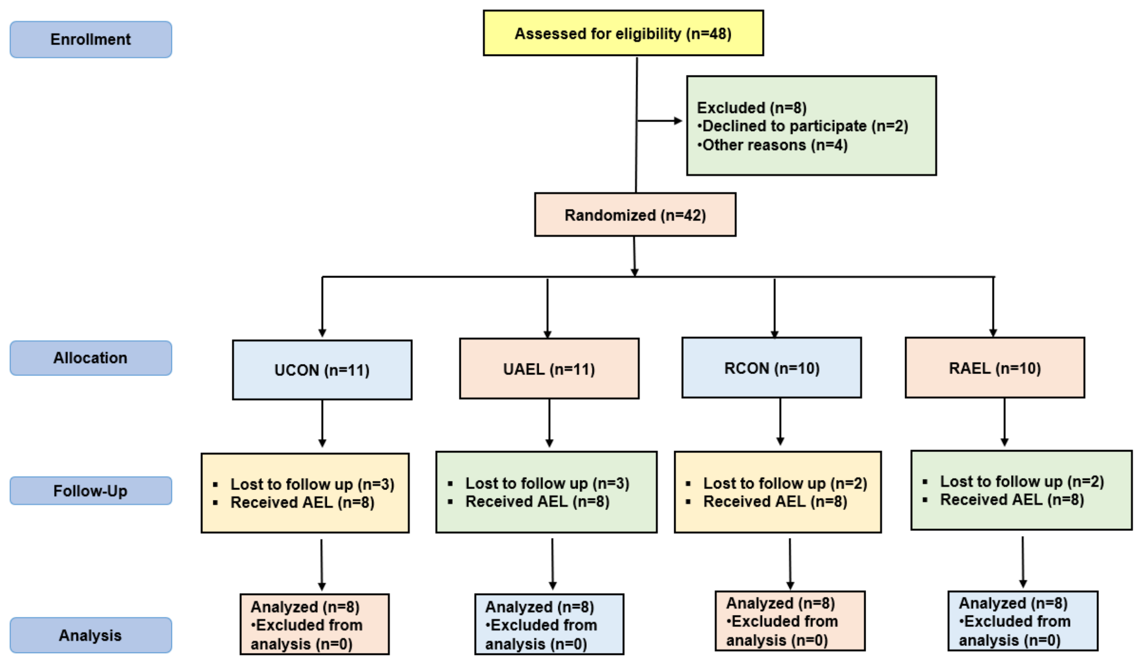

Figure 1. Flowchart of participant recruitment, inclusion and exclusion criteria, and final sample selection.

Table 1. AEL training schedule

Week	Session	Duration	Exercises (AEL)	Load (% BM)	Repetitions	Sets	Recovery (min)	Notes / Tests
Week 1	1–3	60 min	Warm-up (jogging, stretching, leg swings, bodyweight squats); AEL Jump Squats; Weighted Drop Jumps	30	6	3	3–5	Pre-test: Vertical Jump & Agility T-Test
Week 2	4–6	60 min	AEL Jump Squats; Weighted Drop Jumps; Countermovement Jump onto Box	30	6–7	3	3–5	Focus on controlled eccentric movement
Week 3	7–9	60 min	AEL Jump Squats; Weighted Drop Jumps; Weight Release Broad Jump	32	7	3	3–4	Progressive load increase
Week 4	10–12	60 min	AEL Jump Squats; Countermovement Jump onto Box; Single-leg Weight Release Jumps	33	7–8	3	3–4	Integration of unilateral variations
Week 5	13–15	60 min	AEL Jump Squats; Weighted Drop Jumps; Countermovement Jump onto Box; Weight Release Broad Jump	34	8	3	3–4	Higher peak loading phase
Week 6	16–18	60 min	AEL Jump Squats; Weighted Drop Jumps; Single-leg Weight Release Jumps; Countermovement Jump onto Box	35	8	3	3–4	Post-test: Vertical Jump & Agility T-Test

Note. Each session began with a standardized warm-up and concluded with recovery stretching. Training progression was achieved by gradually increasing weekly load and repetitions while maintaining correct form.

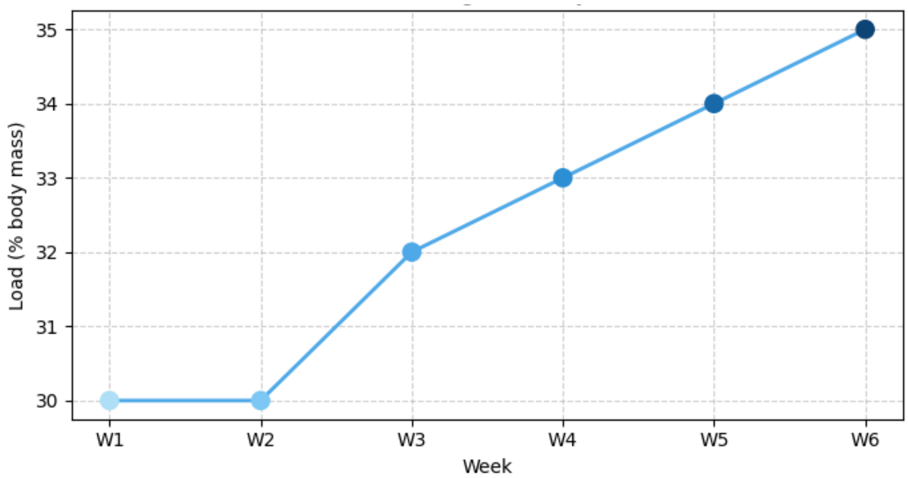

Figure 2. Week-by-week progression of Accentuated Eccentric Loading (% body mass).

rater consistency was maintained by assigning a single experienced examiner to each test across all sessions. Participants were asked to avoid strenuous physical activity during the 24 hours prior to testing.

Explosive Strength. Lower-body explosive strength was assessed using the Vertical Jump Test. Standing reach height and jump reach height were recorded with a standard vertical-jump apparatus, and vertical jump height (cm) was calculated as the difference between the two values. The test is widely applied in sport science and provides reliable indicators of lower-limb power in athletic populations [27].

Agility. Agility was evaluated using the Agility T-Test, which consists of forward sprinting, lateral shuffles, and backward running to measure multidirectional change-of-direction speed. Time was recorded with timing gates or a stopwatch, and the best result of three valid attempts was used for analysis. The test shows high test–retest reliability (ICC ≈ 0.98) and acceptable validity for agility/change-of-direction measurement [28].

Statistical Analysis

Pre-test and post-test scores for vertical jump and agility performance were analyzed using parametric procedures. Descriptive statistics (mean ± standard deviation) were calculated to summarize group data. Within-group change was evaluated using paired sample t-tests. Between-group comparison of post-test scores was performed using Analysis of Covariance (ANCOVA), with pre-test values entered as covariates for group adjustment. Post-hoc pairwise comparisons based on estimated marginal means were conducted to identify differences between RAEL, RCON, UAEL, and UCON. Effect size was expressed as partial eta squared (ηp^2), with 0.01, 0.06, and 0.14 interpreted as small, medium, and large magnitudes [29]. Statistical significance was accepted at $p < 0.05$. All analyses were completed using standard statistical software.

Results

Table 2 presents the pre- and post-intervention values for vertical jump height and agility time obtained from the paired t-test analysis.

Table 2. Pre- and post-test comparison of vertical jump and agility (paired t-test)

Variable	Test phase	Mean ± SD	t	p-value
Vertical Jump (cm)	Before	41.59 ± 12.09	8.69	0.00
	After	44.18 ± 12.02		
Agility (s)	Before	11.12 ± 0.71	5.59	0.00
	After	10.55 ± 0.68		

The table summarizes the changes in performance following the six-week AEL training program. After the training period, vertical jump performance improved, indicating increased explosive lower-limb output, and agility times were reduced, reflecting faster change-of-direction performance. Both outcomes showed statistically significant within-group change, supporting the presence of positive adaptation to the AEL intervention.

Table 3 summarizes the ANCOVA results for vertical jump and agility performance following the intervention. Following adjustment for pre-test values, statistically significant between-group effects were observed for both performance variables ($p < 0.05$). Vertical jump analysis indicated a large effect size, reflecting a considerable proportion of explained variance. Similarly, agility outcomes showed a large effect magnitude, suggesting that the intervention meaningfully influenced change-of-direction performance.

Table 3. Results of ANCOVA for Vertical Jump and Agility Performance

Variable	SS	F value	p-value	η^2
Vertical Jump	56.63	19.80	0.000	0.68
Agility	3.34	10.37	0.000	0.53

Note: SS – Sum of Squares; η^2 – Partial Eta Squared.

Table 4 reports the post-hoc pairwise comparisons among the four treatment groups based on estimated marginal means for vertical jump and agility performance. Post-hoc comparison results show clear differences between eccentric-loaded and control groups. Rural AEL (RAEL) demonstrated greater vertical jump gains than its rural control counterpart, while Urban AEL (UAEL) outperformed the urban control group. Differences between UAEL and RAEL were smaller, indicating comparable training responses across environments. For agility, RAEL showed faster completion time than RCON, and UAEL performed better than UCON. The contrast between UAEL and RAEL was not statistically distinct, suggesting similar directional improvement in both settings. Overall, AEL interventions produced superior outcomes relative to control groups, with UAEL showing the strongest relative advantage within its environment, while RAEL also achieved meaningful performance enhancement.

Table 4. Post-hoc pairwise comparisons of treatment groups

Variable	Group (I)	Group (J)	Mean Diff. (I–J)	Std. Error	Sig.
Vertical Jump	RAEL	RCON	2.132*	.55	.001
		UAEL	-1.176*	.50	.027
	UAEL	UCON	3.299*	.49	.000
		RAEL	1.176	.50	.027
Agility	RAEL	RCON	-.501*	.17	.009
		UAEL	.266	.15	.107
	UAEL	UCON	-.753*	.17	.000
		RAEL	-.266	.15	.107

Note. Estimated marginal means used for vertical jump and agility outcomes. Mean differences marked * indicate significance at $p < 0.05$.

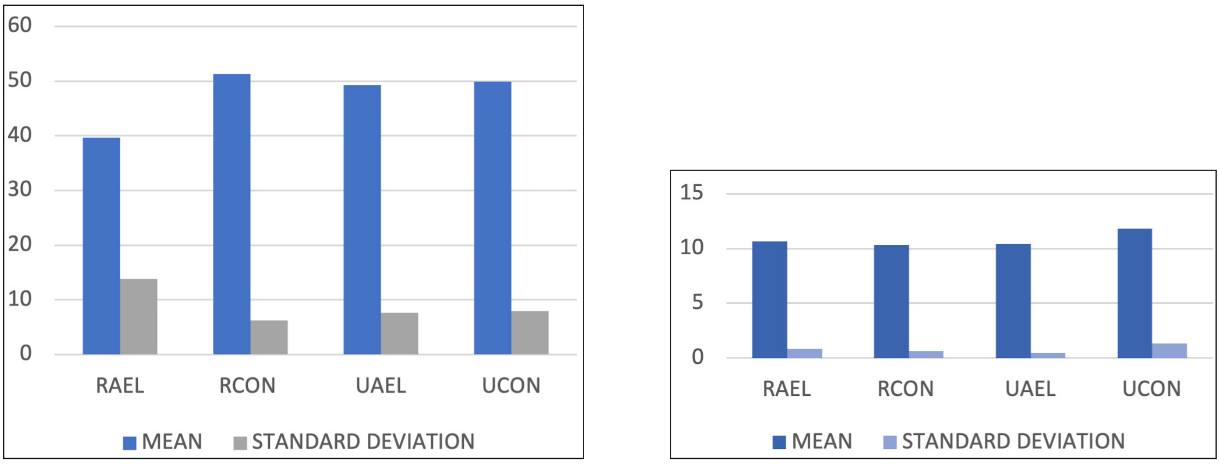

Figure 3. Comparison of Vertical Jump Performance Across Groups (RAEL, RCON, UAEL, UCON) Showing Mean and Standard Deviation

Figure 3 illustrates the comparison of vertical jump performance among the four groups (RAEL, RCON, UAEL, UCON), displaying mean values with associated standard deviations. Visual comparison indicates higher jump performance in the AEL-trained groups relative to their control counterparts. The separation between AEL and non-AEL conditions reflects the influence of eccentric loading on explosive strength, and the profiles of RAEL and UAEL appear broadly similar, suggesting comparable training response patterns across environments.

Discussion

This study examined the effects of AEL training on explosive strength and agility in collegiate basketball players. Significant improvement was observed in both variables following six weeks of progressive eccentric-based training. The findings support the hypothesis that AEL promotes greater adaptation in explosive strength and agility compared with conventional training, indicating that eccentric overload is an effective method for enhancing performance qualities relevant to basketball. A notable contribution of this work is the evaluation of AEL across rural and urban training settings, a dimension rarely addressed in previous literature. Many existing studies were conducted under controlled laboratory conditions or in high-performance environments that do not reflect the constraints faced by athletes training with limited equipment or infrastructure. The similar gains observed in both rural and urban groups suggest that AEL can be implemented successfully in settings with restricted resources. This is particularly relevant for South Asian athletes, where variability in training conditions is common and accessible intervention methods are required.

The improvement in vertical jump height reflects the established capacity of eccentric loading to enhance force production and mechanical efficiency. Eccentric contraction promotes structural and neural adaptations, including increased fascicle length, greater sarcomere number and hypertrophy of type II fibers, which allow muscles to tolerate higher external loads than during concentric actions [4, 6, 30]. These changes support the stretch–shortening cycle function and enable more effective transfer of stored elastic energy into concentric output [10, 28]. The present findings correspond with those reported by Aboodarda et al. [10], who observed enhanced jump performance when additional eccentric load was applied during drop jumps. Douglas et al. also demonstrated that eccentric-emphasized resistance training produced greater strength and power gains in comparison with traditional resistance methods when total work was matched [31]. Overall, the observed increase in vertical jump height suggests development in neuromuscular coordination, elastic energy utilization and concentric force expression following AEL exposure.

Improvement in agility performance following AEL training suggests enhanced capacity for movement control, deceleration and direction change during basketball-specific actions. Eccentric strength contributes to agility development due to its role in force absorption and redirection [32]. The reduction in agility T-test time observed in this study aligns with findings by Zhang et al. [33], who reported that eccentric-focused training improves movement speed through braking force control and motor unit coordination. Similar responses have been documented in relation to speed and agility outcomes under plyometric protocols with eccentric emphasis, supporting the concept that eccentric stimuli facilitate efficient force transition during directional changes [2].

The comparable outcomes observed in rural and urban AEL groups indicate similar physiological adaptations across settings with different resource levels. This suggests that agility improvements from AEL are influenced primarily by neuromuscular factors rather than training infrastructure, consistent with observations reported by Armstrong et al. [8]. Accordingly, AEL can be applied in various environments using basic external loading implements such as weight releasers or weighted vests.

AEL can produce measurable improvements in performance within a relatively short training period. In comparison with more complex or combined methods, AEL alone is capable of improving explosive ability without advanced equipment or long adaptation phases. Gu et al. [35] reported comparable gains in lower-body power and strength using AEL-based countermovement and drop-jump protocols, indicating that this method can be applied effectively across different plyometric formats. The present findings support this evidence within a collegiate basketball cohort. For applied practice, a six-week mesocycle of AEL may serve as a practical in-season option to enhance vertical and multidirectional explosiveness.

Further work incorporating electromyography, force-plate analysis or ultrasonography could clarify how AEL influences muscle activation, tendon stiffness and fascicle architecture [31, 36]. Maeo et al. [36] noted that contraction velocity affects the extent of neuromuscular adaptation during eccentric loading, although this aspect remains under-examined in basketball. The combination of AEL with complementary approaches, including plyometric, resistance or complex training, may produce additive effects, as suggested by Flórez Gil et al. [37]. Examination of such integrated models would help define the position of AEL within a broader performance-development structure.

The findings of this work indicate that eccentric-based loading can influence performance attributes relevant to basketball within a short training cycle. The response pattern observed across rural and urban groups suggests that adaptation depends more on neuromuscular mechanisms than on training infrastructure, which expands the scope for practical application in varied environments. AEL may therefore be incorporated into basketball preparation as a functional conditioning option, providing a basis for further refinement of prescription variables and integration within broader training models.

Limitations and Future Directions

Several limitations should be considered. The six-week duration restricts interpretation of long-term adaptation or retention effects, although it is sufficient for identifying initial performance changes. Longer studies are required to determine whether continued AEL exposure leads to sustained improvement or performance stabilization. The field-based measures used in this study, including vertical jump and the agility T-test, are practical and reflect sport-specific demands, yet they do not provide information on neuromuscular mechanisms. The sample size and inclusion of only male participants also limit generalization to other groups. Future work should incorporate female athletes and different performance levels to improve population coverage. Further research may also examine loading intensity, contraction velocity and exercise selection, as well as evaluate AEL use in other sports such as volleyball and handball.

Conclusions

This study indicates that Accentuated Eccentric Loading (AEL) improves explosive strength, agility and shooting-related performance in basketball players, with similar responses in rural and urban training environments. The six-week AEL protocol (30–35% body mass) likely enhanced stretch–shortening cycle function, eccentric force capacity and motor unit recruitment, which contributed to performance improvement relative to conventional training. While the findings are constrained by sample size and intervention duration, they suggest that AEL can be incorporated into basketball preparation using basic external loading implements.

Conflict of Interest

The authors report no conflict of interest.

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ORIGINAL ARTICLE

Effects of an 8-week core training program on COP-based postural sway and functional performance in male amateur soccer players

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Abstract

Background and Study Aim Core training is applied in athletic preparation to improve movement control and physical capacity. Postural stability is often assessed through balance tasks and force-platform indicators that reflect neuromuscular control. Although various training approaches are used, their relative efficiency in modifying postural sway and functional performance remains a point of practical interest. Therefore, the present study examined the effects of an eight-week core training program on change of direction, vertical jump, sprint, and center-of-pressure (COP) postural sway performance in amateur soccer players.

Material and Methods Thirty male soccer players were randomly assigned to an experimental group (n = 15) and to a control group (n = 15). The experimental group completed a core training program three times per week over a period of eight weeks, giving a total of 24 training sessions. The control group continued regular training without additional core exercises. Performance testing consisted of 30 m sprint, change of direction and vertical jump assessments conducted before and after the intervention. Postural sway was measured on a force platform under two visual conditions, eyes open and eyes closed. Each condition was tested in double leg stance for three trials of 30 seconds, and center of pressure values were recorded for anterior posterior, medial lateral and total sway.

Results After Bonferroni correction, only vertical jump performance showed significant within group improvement in the core training group (pre 41.57 ± 2.09 cm, post 42.02 ± 1.94 cm, $p < 0.001$). No significant within group changes were observed in 30 m sprint (pre 4.34 ± 0.11 s, post 4.31 ± 0.10 s, $p = 0.042$) or change of direction performance (pre 15.84 ± 0.15 s, post 15.82 ± 0.16 s, $p = 0.036$) after correcting for multiple comparisons. In between group comparisons, the core training group demonstrated greater improvement than the control group in vertical jump performance (post 42.02 ± 1.94 cm vs 40.73 ± 1.03 cm, $p = 0.035$, ES = 0.83) and showed favorable although not statistically confirmed reductions in change of direction time. No significant differences between groups were found for sprint performance.

Conclusions An eight-week core training program improved physical performance and postural stability in amateur soccer players. These findings indicate the value of incorporating core stabilization exercises to enhance neuromuscular performance among amateur soccer athletes.

Keywords: core training, postural sway, change of direction, vertical jump, sprint performance

Introduction

Core training is a common element of athletic preparation and supports the body's ability to transfer force and maintain segmental control during movement. Improved trunk stability may enhance postural alignment, reduce compensatory motion, and provide a more efficient base for sport-specific actions. As postural sway reflects the interaction of muscular control, balance, and sensory feedback, its optimization can influence the execution of sprints, jumps, and rapid changes of direction. In this context, examining how systematic core exercise affects functional performance parameters offers a practical perspective for training design. This is particularly relevant in sports that involve continuous changes in speed, direction, and body positioning.

Soccer, one of the most widely played sports globally, attracts a diverse range of male and female participants with varying levels of skill [1]. Modern soccer places higher requirements on the physical fitness and skills of athletes. In a soccer game, performance components such as running velocity, acceleration, deceleration, dribbling, passing and tackling require athletes to have good coordination and postural control skills [2].

Strength training is widely acknowledged as a method for improving athletes' physical performance [3, 4, 5]. Recently, core training (CT)

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has received increasing attention in the literature as it is considered relevant to both daily activities and sport-related performance [6]. The core is described as a muscular box defined by the abdominals, paraspinals, gluteals, the diaphragm, the pelvic floor, and the hip girdle muscles working in concert [7]. These muscles contribute to stabilizing the spine and pelvis and provide proximal stability that supports distal mobility and limb function in daily activities and sports. Core functionality also affects balance, stability, and movement efficiency. Efficient function of the core muscles supports accurate transfer and control of force to the upper and lower extremities [8].

Core stability reflects the coordinated activation of trunk muscles that maintain control of the spine and pelvis during movement [8]. Increased core stability supports physical performance through several physiological and biomechanical mechanisms, including improved force transmission, intersegmental coordination, proprioceptive feedback, and postural control [9]. By functioning as a central force-transfer hub between the upper and lower extremities, the core musculature enables more efficient energy transfer during high-speed, power-based movements such as sprinting, jumping, and change of direction [10]. From a postural control perspective, enhanced core stability reduces center-of-pressure sway and improves balance by increasing the effectiveness of proprioceptive inputs. Chaari et al. reported that greater core stability is associated with reductions in anteroposterior and mediolateral sway [11]. Taken together, these mechanisms indicate that core stability enhances trunk control and provides a biomechanical foundation that supports multiple components of athletic performance.

Many studies have reported positive effects of core training on sport performance across different disciplines, including improvements in kicking ability, balance, strength, and technical skills in karate, volleyball, and handball players [12, 14, 15]. Similar findings have been shown for distal limb performance in striking tasks, football-specific skills, soccer performance, and balance control in basketball majors [13, 16, 17, 18]. However, the relationship between core training and performance outcomes such as postural sway has not been examined in detail in the literature [19].

Analysis of research findings has shown that core training can enhance various components of athletic performance, including balance, strength expression, and the efficiency of force transfer between body segments. Researchers emphasize that trunk stability contributes to postural control and supports movement execution in actions that require rapid acceleration, deceleration, and directional change. However, the majority of the studies focus on elite athletes, with only a limited number conducted on amateur soccer players. This makes the relationship between core training, postural sway, and functional performance a relevant area for applied evaluation that warrants further targeted examination. Accordingly, the purpose of this research was to examine the effects of an eight-week core training program on change of direction (COD), vertical jump, sprint, and postural sway performance in amateur soccer players.

Materials and Methods

Participants

The study included 30 male amateur soccer players from the Ankara region. The sample size was determined using G*Power (17) based on a priori power analysis for a two-tailed t-test, assuming a medium effect size (Cohen's d = 0.50), an alpha level of 0.05, and a statistical power (1−β) of 0.80. Sample size justification: the power analysis indicated that a total of 30 participants would provide sufficient statistical power and generalizability. Accordingly, 30 players were recruited and randomly assigned to either the study group (n = 15) or the control group (n = 15).

Exclusion criteria included a history of musculoskeletal injury, surgical intervention, or lower-limb pain within the past six months; neurological, vestibular, or balance disorders; any medical condition that might affect postural control; regular use of medication influencing neuromuscular function; and missing more than 10% of training sessions during the intervention period. All participants had competed in amateur league matches for at least two years.

The control group continued regular soccer training three times per week during the eight-week intervention, with each session lasting approximately 120 minutes. Training consisted of routine technical drills, tactical gameplay, and endurance-based conditioning prescribed by team coaches. No additional core, resistance, or neuromuscular exercises were introduced. Descriptive information for the study group is presented in Table 1.

Research Design

Participants were randomly divided into two groups: the study group (n = 15) and the control group (n = 15). Random assignment was conducted using a computer-generated random number list in Microsoft Excel. A simple randomization procedure was applied, without block randomization or stratification. The randomization sequence was prepared by an independent researcher who was not involved in data collection or analysis. Allocation concealment was ensured using sequentially numbered, opaque, sealed envelopes, which were opened only after baseline testing.

To minimize potential bias, all performance

Table 1. Descriptive information of the study group.

Group	Variables	N	X̄	Ss	Min	Max
Study Group	Age (years)	15	21.47	1.35	19	23
	Body weight (kg)	15	68.80	4.14	63	78
	Body height (m)	15	1.75	0.05	1.66	1.84
	Body mass index (BMI)	15	22.48	1.63	19.93	25.77
Control Group	Age (years)	15	20.13	1.50	18	23
	Body weight (kg)	15	65.13	3.22	62	73
	Body height (m)	15	1.77	0.03	1.73	1.83
	Body mass index (BMI)	15	20.71	1.14	18.51	22.39

Note. X̄ = mean; Ss = standard deviation; Min = minimum value; Max = maximum value

tests (sprint, change of direction, vertical jump, and postural sway) were administered by assessors who were blinded to group allocation. Participants were instructed not to disclose their group assignment to the evaluators. Training adherence was monitored using attendance logs completed by an independent coach at each training session. All participants completed the 8-week intervention and post-tests, representing a 100% retention rate. Training adherence was calculated as an average of 22.8 ± 1.2 out of 24 sessions (95% compliance). No adverse events or injuries were reported during the study.

The training program was implemented three times per week for eight weeks. The study group performed additional core training exercises alongside regular team practices, whereas the control group continued only routine soccer training. Measurements were conducted twice, before and after the intervention (pre-test and post-test). To familiarize participants with the testing procedures, a practice session was held prior to data collection. All tests were carried out on a grass field under similar environmental conditions and at the same time of day to reduce circadian variability. Participants were instructed to wear identical sportswear and footwear during all testing sessions.

The athletes received essential information regarding nutrition and rest practices throughout the training and testing periods. One week before the first training session, the exercises planned for the 8-week program were individually practiced and corrected until participants could perform them properly (minimizing spinal loading, maintaining correct breathing, and activating the transverse abdominis and multifidus muscles) [17, 18]. Prior to each session, athletes performed a 15-minute dynamic warm-up followed by stretching to improve flexibility, particularly in the lumbo-pelvic region, to reduce the risk of spinal injuries or lower back pain. Exercise intensity, duration, repetitions, and volume were gradually increased in line with the principle of progressive overload.

To minimize learning effects during performance testing, both groups underwent the same familiarization protocol. Following a standard warm-up, all participants performed one to two practice trials for each test (sprint, change of direction, vertical jump, and postural sway) using the same devices and instructions as in the actual procedures. These attempts were conducted solely for familiarization and were not included in the analyses. Details of the training program applied to the study group are presented in Table 2.

Exercise Descriptions and Progression

The core training program consisted of eight exercises targeting major core muscle groups. Each exercise was performed with specific durations or repetitions, increasing progressively each week as detailed in Table 2. For static exercises such as plank and side plank, participants maintained a controlled posture focusing on spinal alignment and muscle engagement throughout the prescribed duration. Dynamic exercises including crunch, back extension, Russian twist, hip raise, and bird-dog involved controlled concentric and eccentric muscle actions performed with emphasis on technique and breathing.

The tempo for dynamic movements was approximately two seconds for concentric and two seconds for eccentric phases to enhance neuromuscular control. Progression was ensured by gradually increasing duration for time-based exercises and repetitions for repetition-based movements, while maintaining exercise quality. Rest intervals were also reduced from 90 seconds in Weeks 1–4 to 60 seconds in Weeks 5–8, following the principle of progressive overload.

The progression parameters were structured according to fundamental exercise science principles to allow a gradual weekly increase in training load. During the first four weeks, durations and repetitions increased in a controlled manner to support initial neuromuscular and connective tissue adaptation. From Week 5 onward, shorter

Table 2. Training program (corrected format)

Exercises	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
1-Plank (s)	25×2	25×2	30×2	30×2	40×2	40×2	50×2	50×2
2-Side plank (right) (s)	25×2	25×2	30×2	30×2	40×2	40×2	50×2	50×2
3-Side plank (left) (s)	25×2	25×2	30×2	30×2	40×2	40×2	50×2	50×2
4-Crunch (rep)	20×2	20×2	25×2	25×2	30×2	30×2	35×2	40×2
5-Back extension (rep)	20×2	20×2	25×2	25×2	30×2	30×2	35×2	40×2
6-Russian twist (rep)	25×2	25×2	30×2	30×2	35×2	35×2	40×2	40×2
7-Hip raise (rep)	20×2	20×2	25×2	25×2	30×2	30×2	35×2	35×2
8-Bird dog (s)	25×2	25×2	30×2	30×2	35×2	35×2	40×2	40×2
Rest between sets (s)	90	90	90	90	60	60	60	60

rest intervals were introduced to increase metabolic stress, muscular endurance, and neuromuscular demand. Previous studies indicate that reducing rest duration elevates metabolic load, accelerates local fatigue, and increases demands on stabilizing musculature.

Data Collection Tools: Body height was measured using a wall-mounted Holtain stadiometer (England) with 1 mm accuracy, and body weight was measured with a Tanita BC480 digital scale (Japan). Body mass index (BMI) was calculated by dividing weight in kilograms by the square of height in meters (kg/m^2), following the World Health Organization (WHO) standard.

30 m Sprint Test: Sprint times were recorded using infrared photocell gates (Witty-Microgate, Italy). Athletes started each sprint 30 cm behind the starting line and were instructed to run through the timing gates at maximum speed. Each athlete completed two attempts, and the best time was retained for analysis. A 3-minute rest interval was provided between repetitions.

Illinois Change of Direction Test: A test track measuring 5 m in width and 10 m in length was set up on a grass soccer field, with three cones placed along the mid-section at 3.3 m intervals. Change of direction performance was measured using infrared photocell gates. Athletes started 1 m behind the starting line and were instructed to complete the track at maximum effort. Each participant performed two attempts, and the best time was recorded in seconds.

Vertical Jump Test: Vertical jump performance was assessed using two OptoJump devices (Microgate, Italy) placed opposite each other. Previous studies have shown that the OptoJump photoelectric system provides highly reliable estimates of jump height (ICC = 0.99, 95% CI 0.97–0.99; $p < 0.001$) [20, 21]. Participants performed the test with their hands on their hips, remaining still until prompted by a verbal signal. They were instructed to jump as quickly and as high as possible, minimizing the transition between the eccentric and concentric phases. The depth of the countermovement was self-selected, and participants were advised to avoid movement during the flight phase [22]. Attempts were deemed invalid if athletes failed to maintain hands on hips at take-off or if they raised, spread, or pulled their knees or feet upward or outward. Each participant completed three attempts with a one-minute rest interval between trials.

Postural Sway Measurement: Postural sway was assessed using a Kistler® force platform (Switzerland). A measurement protocol was created in the *Body Sway* module, and sway values were obtained during a static balance test. Measurements were performed in a double-leg stance with eyes open and eyes closed. Participants completed 2–3 minutes of familiarization trials prior to testing to reduce learning effects. After a five-minute warm-up, athletes were instructed to focus on a fixed point located 1 m in front of them, remain as still as possible, and keep their arms relaxed at their sides. Standing at the center of the force platform, participants positioned their feet in the anterior–posterior (A–P) direction along the Y-axis and medial–lateral (M–L) direction along the X-axis, with toes pointing forward (+Y). The test began following a verbal countdown (3–2–1). Each participant performed three 30-second trials with eyes open and three 30-second trials with eyes closed. A two-minute rest interval was provided between trials to minimize fatigue-related effects. The reliability and validity of Kistler® force platforms for postural sway assessment have been demonstrated in previous studies, supporting their suitability for balance analysis.

Statistical Analysis

Data management and missing data: Prior to hypothesis testing, all datasets were screened for outliers, input errors, and missing records. Values exceeding ±3 SD from the group mean were cross-checked against original measurement files. Missing or invalid observations related to primary outcome measures were handled using complete-case analysis; participants with missing data for a specific variable were excluded from the corresponding comparison. No imputation procedures were applied.

Analytical procedures: Data analysis was performed using SPSS version 29.0 (IBM Corp., Armonk, NY, USA). Normality was assessed using the Shapiro–Wilk test, supported by skewness and kurtosis values. Variables with $p > 0.05$ and skewness/kurtosis values within ±1.0 were considered normally distributed and were evaluated using parametric statistics. When normality assumptions were violated, non-parametric alternatives were used. Within-group comparisons were conducted using paired t-tests or the Wilcoxon signed-rank test. Between-group differences were assessed using independent t-tests or the Mann–Whitney U test. Effect sizes were calculated to determine the magnitude of differences. For parametric outcomes, Cohen's d values of 0.2, 0.5, and 0.8 represented small, medium, and large effects. For non-parametric outcomes, effect size r was calculated as $r = Z / \sqrt{N}$, with thresholds of 0.1, 0.3, and 0.5 indicating small, medium, and large effects. Statistical significance was set at $p < 0.05$, and Bonferroni adjustments were applied to control for multiple comparisons.

Results

Pre- and post-test values for change of direction, 30 m sprint, and vertical jump performance in both groups are presented in Table 3. The table includes mean scores, standard deviations, effect sizes, p-values, and Bonferroni-adjusted significance outcomes for each variable.

Table 3 shows that the study group demonstrated improvements in change of direction ($p = .036$, ES = 0.13) and 30-m sprint performance ($p = .042$, ES = 0.29), as well as a statistically significant increase in vertical jump height ($p < .001$, ES = 0.22). After Bonferroni adjustment ($\alpha = 0.0083$), only the improvement in vertical jump performance remained statistically significant. No significant changes were observed in the control group. These results indicate that the eight-week core training program had the greatest effect on vertical jump performance, whereas changes in sprint and change of direction ability were small and not statistically meaningful after correction.

Postural sway outcomes for anterior–posterior, medial–lateral, and total sway under eyes-open and eyes-closed conditions are presented in Table 4. The table summarizes pre- and post-intervention values, Wilcoxon test statistics, p-values, effect sizes, and Bonferroni-adjusted significance results for the experimental group.

Table 4 shows that in the experimental group, statistically significant and large reductions were observed in postural sway under eyes-closed conditions, including anterior–posterior sway ($p = .001$, $r = 0.84$), medial–lateral sway ($p = .001$, $r = 0.87$), and total sway ($p = .003$, $r = 0.76$). These improvements

Table 3. Paired t-test results for pre- and post-test measurements of COD, 30 m sprint, and vertical jump in study and control groups.

Variables	Group	Measurement	X̄	Ss	t	p	ES	Bonferroni α	Significant
COD (s)	Study	pre-test	15.84	0.15	2.320	.036	0.129	0.0083	No
		post-test	15.82	0.16					
	Control	pre-test	15.87	0.16	-1.468	.164	0.063	0.0083	No
		post-test	15.88	0.16					
30 m sprint (s)	Study	pre-test	4.34	0.11	2.244	.042	0.285	0.0083	No
		post-test	4.31	0.10					
	Control	pre-test	4.37	0.12	-1.164	.264	0.087	0.0083	No
		post-test	4.38	0.11					
Vertical jump (cm)	Study	pre-test	41.57	2.09	-2.271	.000	0.22	0.0083	Yes
		post-test	42.02	1.94					
	Control	pre-test	40.88	1.08	1.643	.123	0.142	0.0083	No
		post-test	40.73	1.03					

Table 4. Pre-test and post-test postural sway Wilcoxon test results of the experimental group

Variables (mm)	Measurement	X̄	Ss	Z	p	ES (r)	Bonferroni α	Significant
Anterior-Posterior Sway (mm) (eyes closed, double-leg stance)	pre-test	132.56	49.55	-3.237	.001	0.84	0.0083	Yes
	post-test	87.84	28.66					
Medial-Lateral Sway (mm) (eyes closed, double-leg stance)	pre-test	56.18	17.13	-3.351	.001	0.87	0.0083	Yes
	post-test	42.41	12.59					
Total Sway (mm) (eyes closed, double-leg stance)	pre-test	290.24	84.06	-2.953	.003	0.76	0.0083	Yes
	post-test	210.51	85.10					
Anterior-Posterior Sway (mm) (eyes open, double-leg stance)	pre-test	124.56	61.45	-2.499	.012	0.65	0.0083	No
	post-test	112.14	65.85					
Medial-Lateral Sway (mm) (eyes open, double-leg stance)	pre-test	51.85	21.71	-3.124	.002	0.81	0.0083	Yes
	post-test	41.70	21.23					
Total Sway (mm) (eyes open, double-leg stance)	pre-test	236.74	84.35	-2.045	.041	0.53	0.0083	No
	post-test	216.89	85.60					

Note: Effect size calculated as $r = Z / \sqrt{N}$.

remained significant after Bonferroni adjustment (α = 0.0083). Under eyes-open conditions, a significant decrease was found only in medial–lateral sway (p = .002, r = 0.81), while changes in anterior–posterior sway (p = .012, r = 0.65) and total sway (p = .041, r = 0.53) did not meet the corrected significance threshold. These findings indicate that the training program produced the greatest postural stability improvements when visual input was removed, suggesting enhanced proprioceptive control and neuromuscular regulation.

Postural sway outcomes for the control group under eyes-open and eyes-closed conditions are presented in Table 5. The table includes pre- and post-test values, Wilcoxon Z statistics, p-values, effect sizes, and Bonferroni-adjusted significance results, allowing comparison with changes observed in the experimental group.

Table 5 shows that no statistically significant differences were found between pre- and post-test postural sway values in the control group. With eyes closed, anterior–posterior (p = .320, r = 0.26), medial–lateral (p = .112, r = 0.41), and total sway (p = .307, r = 0.26) scores did not change meaningfully. Similarly, under eyes-open conditions, anterior–posterior (p = .125, r = 0.40), medial–lateral (p = .256, r = 0.29), and total sway (p = .233, r = 0.31) outcomes showed no significant differences. After Bonferroni adjustment (α = 0.0083), none of the results reached statistical significance. These findings indicate that regular soccer training performed by the control group did not produce measurable improvements in balance or postural sway.

Between-group comparisons of change of direction, 30 m sprint, and vertical jump performance are summarized in Table 6. The table presents independent t-test results for pre- and post-intervention measurements, including mean values, standard deviations, p-values, and effect sizes for both the experimental and control groups.

Table 6 shows that only post-test vertical jump performance differed significantly between the experimental and control groups (p = .035, ES = 0.83). No significant between-group differences were observed in COD (pre-test p = .540, ES = 0.19; post-test p = .317, ES = 0.38) or 30-m sprint performance (pre-test p = .414, ES = 0.26; post-test p = .115, ES = 0.67). These results indicate that the eight-week core training program led to greater improvements in vertical jump height compared with the control group, whereas changes in COD and sprint performance were small and not statistically meaningful.

Between-group comparisons of postural sway values under eyes-open and eyes-closed conditions are presented in Table 7. The table reports Mann–Whitney U test results for pre- and post-test measurements, including mean ranks, U statistics, p-values, and significance after Bonferroni adjustment for the experimental and control groups.

Table 7 shows that no statistically significant differences were observed between the experimental and control groups in any postural sway variable under eyes-closed or eyes-open conditions after Bonferroni adjustment (α = 0.0042). Although

Table 5. Pre-test and post-test postural sway Wilcoxon test results of the control group

Variables (mm)	Measurement	X̄	Ss	Z	p	ES (r)	Bonferroni α	Significant
Anterior-Posterior Sway (eyes closed, double-leg stance)	pre-test	122.60	48.49	-.994	.320	0.26	0.0083	No
	post-test	123.41	49.17					
Medial-Lateral Sway (eyes closed, double-leg stance)	pre-test	68.67	47.43	-1.590	.112	0.41	0.0083	No
	post-test	67.04	40.04					
Total Sway (eyes closed, double-leg stance)	pre-test	288.56	87.71	-1.023	.307	0.26	0.0083	No
	post-test	295.21	95.48					
Anterior-Posterior Sway (eyes open, double-leg stance)	pre-test	165.33	89.32	-1.533	.125	0.40	0.0083	No
	post-test	165.28	88.91					
Medial–Lateral Sway (eyes open, double-leg stance)	pre-test	76.09	47.11	-1.136	.256	0.29	0.0083	No
	post-test	71.94	37.41					
Total Sway (eyes open, double-leg stance)	pre-test	282.70	91.37	-1.193	.233	0.31	0.0083	No
	post-test	284.25	90.73					

Note: Effect size calculated as r = Z / √N.

Table 6. Independent t-test results for pre-test and post-test measurements of COD, 30 m sprint, and vertical jump

Variables	Measurement	Study Group (X̄ ± Ss)	Control Group (X̄ ± Ss)	t	p	ES
COD (s)	Pre-test	15.84 ± 0.15	15.87 ± 0.16	0.620	.540	0.19
	Post-test	15.82 ± 0.16	15.88 ± 0.16	0.101	.317	0.38
30 m Sprint (s)	Pre-test	4.34 ± 0.11	4.37 ± 0.12	-0.829	.414	0.26
	Post-test	4.31 ± 0.10	4.38 ± 0.11	-0.163	.115	0.67
Vertical Jump (cm)	Pre-test	41.57 ± 2.09	40.88 ± 1.08	1.132	.270	0.42
	Post-test	42.02 ± 1.94	40.73 ± 1.03	2.257	.035	0.83

Table 7. Mann–Whitney U test results for pre-test and post-test postural sway measurements in the experimental and control groups

Variables (mm)	Measurement	Study Group (X̄ ± Ss)	Control Group (X̄ ± Ss)	U	p	ES (r)	Bonferroni α	Significant
Anterior–Posterior sway (eyes closed, double-leg stance)	Pre-test	132.56 ± 49.55	122.60 ± 48.49	93.00	.41	0.14	0.0042	No
	Post-test	87.84 ± 28.66	123.41 ± 49.17	64.00	.04	0.36	0.0042	No
Medial–Lateral sway (eyes closed, double-leg stance)	Pre-test	56.18 ± 17.13	68.67 ± 47.43	110.00	.91	0.02	0.0042	No
	Post-test	42.41 ± 12.59	67.04 ± 40.04	65.00	.04	0.36	0.0042	No
Total sway (eyes closed, double-leg stance)	Pre-test	290.24 ± 84.06	288.56 ± 87.71	111.50	.96	0.00	0.0042	No
	Post-test	210.51 ± 85.10	295.21 ± 95.48	62.50	.03	0.37	0.0042	No
Anterior–Posterior sway (eyes open, double-leg stance)	Pre-test	124.56 ± 64.45	165.33 ± 89.32	94.00	.44	0.14	0.0042	No
	Post-test	112.14 ± 65.85	165.28 ± 88.91	62.00	.03	0.38	0.0042	No
Medial–Lateral sway (eyes open, double-leg stance)	Pre-test	51.85 ± 21.71	76.09 ± 47.11	79.00	.16	0.25	0.0042	No
	Post-test	41.70 ± 21.33	71.94 ± 37.41	54.50	.01	0.44	0.0042	No
Total sway (eyes open, double-leg stance)	Pre-test	236.74 ± 84.35	282.70 ± 91.37	78.00	.15	0.26	0.0042	No
	Post-test	216.89 ± 85.60	284.25 ± 90.73	61.50	.03	0.38	0.0042	No

Note: Effect size calculated as r = Z / √N.

several post-test outcomes demonstrated small-to-moderate effect sizes (r = 0.14–0.44), none exceeded the corrected significance threshold. Pre-test values likewise showed no meaningful differences between groups, indicating comparable baseline balance characteristics prior to the intervention. These findings suggest that, despite a trend toward lower sway magnitudes in the experimental group, between-group differences did not reach statistical significance.

Discussion

The present study aimed to examine whether an eight-week core training program would influence change of direction, 30-m sprint, vertical jump performance, and postural sway in soccer players. The results showed that vertical jump performance improved in the training group and remained statistically significant after Bonferroni adjustment. Improvements in change of direction and sprint times were small and did not reach statistical significance after correction. Postural sway measures with eyes closed demonstrated clear reductions in sway amplitude within the training group, while between-group comparisons did not reveal statistically meaningful differences. Together, these findings indicate that the core-centered intervention was most effective in enhancing jump performance and internal stability control, whereas changes in sprint and directional movement ability were limited.

This study contributes to the existing body of research in three ways. First, it examines the effects of core training on force-platform–based measurements of postural sway in soccer players using controlled experimental design. Second, it evaluates change of direction, sprint time, vertical jump, and balance variables within the same investigation, allowing these outcomes to be interpreted in relation to one another. Third, it focuses on athletes competing at a non-elite level, which extends current findings that have predominantly been drawn from research involving higher-performance groups.

Postural sway measurements indicated that core training was associated with improved balance control. The reduction in anterior–posterior and medial–lateral sway, particularly under eyes-closed conditions, may reflect positive changes in proprioceptive regulation. These outcomes align with reports suggesting that exercises targeting core stability can influence postural balance [23, 24, 25, 26, 27].

The observed results may be considered within the context of motor control concepts. From a dynamic systems viewpoint, core-related adaptations could contribute to more coordinated segmental interactions, which may in turn relate to changes in sprint, jump, and change-of-direction performance. Reductions in sway also suggest more stable integration of feedforward and feedback mechanisms within postural regulation frameworks. Such adaptations may facilitate proximal-to-distal force transfer during movement execution, allowing athletes to perform lower-limb actions with a more stable trunk position. In this regard, core training may influence both local stabilization of the trunk and broader control processes relevant to fast movement actions in soccer.

When vertical jump performance was examined, core training was associated with a measurable improvement in this variable. One possible explanation is the involvement of core musculature in the transfer and regulation of force across the upper and lower extremities. Previous research has reported similar outcomes. Doğan and Mendeş [28] observed improvements in vertical jump following an eight-week core program in soccer players, and another study reported increased jump performance in 11–13-year-old players after a ten-week intervention [29]. Although preliminary within-group analyses indicated changes in sprint and change-of-direction performance, these effects were not maintained after Bonferroni adjustment. For this reason, interpretations of sprint and COD outcomes should rely primarily on between-group comparisons. In this regard, the core training group showed more notable changes than the control group, especially in vertical jump height and directional-change outcomes. Taken together, these results suggest that core training alone may not produce pronounced improvements in sprint or COD ability, but may contribute to neuromuscular features relevant to speed-power tasks when integrated with complementary training approaches.

Core training being effective in non-elite soccer players addresses an area that is less represented in previous research. While many studies have concentrated on elite populations [16], the present work examined performance outcomes in amateur players. These findings may be useful for planning training approaches for developing athletes and for structuring programs that target balance, jump capacity, and related neuromuscular components.

Limitations

This study has several limitations. The sample size was relatively small, which limits generalizability and reduces the ability to detect small differences between groups. Although the intervention lasted eight weeks, this duration may be insufficient for observing longer-term neuromuscular adaptations to core training. In addition, several improvements did not remain statistically significant following Bonferroni adjustment, which indicates that the stability of some outcomes should be interpreted cautiously. Future studies may benefit from larger samples, extended intervention periods, and the inclusion of additional neuromuscular measures to examine long-term effects more comprehensively. The characteristics of the sample also impose restrictions. The study involved only male amateur soccer players, meaning that findings may not be directly transferable to female players, different age groups, or athletes from other performance levels. The use of multiple performance variables introduces the potential for both Type I and Type II error. While Bonferroni correction helped reduce the likelihood of Type I error, it simultaneously increased the probability of Type II error, resulting in the possibility that real effects were not detected. For this reason, the outcomes should be interpreted with consideration of the multiple comparison structure used.

Practical Applications

The findings of this study suggest that core training may be considered as a component of physical preparation in soccer, particularly when the goal is to improve jump-related outputs and postural stability. Coaches and practitioners may incorporate structured core exercises into regular training cycles to support trunk control, improve balance regulation under reduced visual feedback, and assist in preparing athletes for actions requiring controlled force transfer. The absence of marked changes in sprint and change-of-direction outcomes indicates that core training may function more effectively when combined with other performance-oriented methods such as plyometrics, short-acceleration drills, and repeated COD practice. Integrating core programs with speed–power training could provide a more complete stimulus for performance development. When planning training loads, practitioners may also consider adjusting intervention duration and progression to target both stability and sport-specific locomotor demands.

Conclusions

The outcomes of this study indicate that core training can be integrated into physical preparation to support postural stability and power-related actions in soccer. These adaptations appear most evident in balance control under reduced visual input and in tasks requiring vertical force production. Improvements in other performance domains were modest, which suggests that core training acts as a complementary rather than a primary performance driver. Taken together, the findings position core training as one element within a broader conditioning framework rather than a stand-alone method for speed or directional movement enhancement. Its value may be realized most effectively when combined with sport-specific drills, power development, and movement-based training progressions. Continued investigation may clarify how the timing, duration, and integration of core work shape its contribution to athlete development over longer cycles.

Consent to Participate

Written informed consent was obtained from all participants prior to data collection.

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Conflict of Interest

The authors declare no conflict of interest.

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ORIGINAL ARTICLE

Effects of the battle shuttlecock game on VO_2max and lob technique in children aged 9–12 years

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Abstract

Background and Study Aim School-based physical education includes structured efforts to maintain physical fitness in children. Various approaches such as non-linear pedagogy, constructivist methods, and physical literacy have been applied to support learning through movement. Despite their application, the relative effectiveness of integrated models that combine technical skill and aerobic development remains a matter of practical interest. This study aims to test the effects of Battle Shuttlecock on students' VO_2max and lob performance while assessing its pedagogical relevance in physical education.

Material and Methods A pretest-posttest quasi-experimental study was conducted with a control group. Participants were elementary school students who took part in extracurricular badminton activities. The experimental group received 14 progressive Battle Shuttlecock sessions. The control group received standard badminton training. VO_2max was measured using the Multistage Fitness Test. Lob shot skills were assessed using the French Clear Test. Additional instruments included Perceived Competence, Mini-PACES, a fidelity checklist, and observations of social, emotional, and cognitive behavior. Data were analyzed using MANCOVA at a significance level of $\alpha = 0.05$.

Results The experimental group showed a significant increase in VO_2max from 38.5 ± 2.9 to 39.1 ± 2.6 ml/kg/min. Lob shot accuracy increased from 55.3 ± 6.7 to 64.2 ± 7.1 points ($p < 0.001$). The control group did not show a significant increase in either variable. The results indicate that Battle Shuttlecock supports learning and improves technical, emotional, and cognitive skills when used consistently. The game had a significant effect on both VO_2max and lob performance.

Conclusions Battle Shuttlecock improved cardiorespiratory fitness and lob technique. It can be used in school programs to support physical, technical, emotional, and cognitive development.

Keywords: game-based learning, aerobic capacity, motor skill acquisition, primary school children, hybrid pedagogy

Introduction

Physical activity in childhood is closely linked to physical development, motor competence, and long-term health outcomes. Despite increasing awareness of its benefits, many children continue to demonstrate low levels of physical fitness, including limited aerobic capacity. These trends are influenced by a combination of lifestyle habits, reduced movement opportunities in school settings, and a lack of age-appropriate physical engagement. As a result, maintaining and improving cardiorespiratory fitness in school-age children remains a complex and relevant challenge within physical education.

One approach to supporting physical development in children involves structured extracurricular sports within elementary schools. These programs contribute to improving physical fitness, motor skills, and aspects of character formation. School-based initiatives have been shown to encourage participation in physical activity, support fitness gains, and promote social-emotional development [1, 2]. The concept of proficiency barriers, proposed by Seefeldt, suggests that mastering fundamental motor skills provides a necessary foundation for the acquisition of more complex sport-specific abilities. This concept has been supported by recent longitudinal research [3]. Within this context, badminton is a widely practiced sport that combines recreational appeal with physical challenge. It engages coordination, agility, endurance, and focus, making it suitable for use in school programs [4].

The lob shot is a fundamental badminton skill that should be developed at an early stage. An effective lob is characterized by a high and long shuttlecock trajectory directed to the back of the opponent's court. This makes it difficult to return and gives the player time to reposition [5]. Mastery of this technique depends on a foundation of physical conditioning, particularly aerobic capacity (VO_2max), as badminton involves prolonged rallies and high-intensity movement [5,6]. At the same time, several studies have reported a decline in children's overall fitness, especially cardiorespiratory

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capacity, over recent decades. This trend highlights the importance of early intervention during the elementary school years [7].

Previous studies have shown that children's VO_2max can improve through structured physical training and high-intensity activity. Meta-analyses have reported that badminton-specific programs, including interval and plyometric training, can enhance aerobic capacity and physical performance [5, 8]. In addition, backward walking has been identified as a useful movement variation. It supports the development of agility, balance, and other physical attributes relevant to badminton [9].

Game-based approaches such as Teaching Games for Understanding (TGfU) and Small-Sided Games (SSG) have served as foundational methods in physical education. However, both approaches have limitations, as they do not fully integrate technical skill development and biomotor capacity into a unified game format [12, 13, 14]. Research on hybrid pedagogical models highlights the importance of combining technical, tactical, and physical components to improve student learning and engagement [15, 16]. In constructivist frameworks, the use of representative learning tasks and adaptive movement challenges is associated with the development of motor competence and movement understanding [17]. Additionally, interventions that promote competence, confidence, motivation, and participation are linked to stronger physical literacy outcomes [18].

Meta-analytic evidence confirms that structured programs incorporating technical, tactical, and physical elements can lead to significant improvements in children's physical development and engagement [12]. Other studies have further emphasized that game-based models which integrate motor skills, aerobic capacity, and sport-specific techniques can support the development of physical literacy from both pedagogical and experiential perspectives [20, 21, 22, 23].

Analysis of research findings has shown that combining technical skill development with aerobic training within a game-based format can enhance student engagement and learning outcomes. Scholars emphasize that hybrid pedagogical models grounded in constructivist principles provide promising strategies for supporting motor competence, motivation, and physical literacy in children. At the same time, the challenge of designing integrated, scalable, and age-appropriate interventions that address both physical and technical development remains. This gap continues to limit the practical application of combined skill-and-fitness programs in school settings and calls for further pedagogical innovation.

Therefore, this study aims to examine the effects of the Battle Shuttlecock game on VO_2max and lob performance among elementary school students, and to assess its pedagogical relevance within a school-based physical education context.

Materials and Methods

Participants

The study involved 32 elementary school students who participated in badminton extracurricular activities at SD Muhammadiyah Pakel, Yogyakarta. They were aged 9–12 years (11 girls and 21 boys). Participation was voluntary. Written informed consent was obtained from the students and from their parents or guardians.

Participants were assigned to the experimental group (n = 16) or the control group (n = 16) using block randomization with a block size of four. The allocation sequence was generated by an automated randomization program operated by an independent third party who was not involved in data collection or intervention delivery. To reduce selection bias, allocation concealment was maintained using sealed opaque envelopes. These envelopes were opened by the coach only after all pre-test assessments had been completed.

A priori power analysis was conducted using G*Power version 3.1 for a twogroup MANOVA with two dependent variables. With an assumed effect size of $f^2(V) = 0.30$ (medium), $\alpha = 0.05$, and power $(1-\beta) = 0.80$, the minimum required sample size was 28 participants. The final sample of 32 participants exceeded this threshold and ensured adequate statistical power. This study received ethical approval from the Research Ethics Committee of Universitas Negeri Yogyakarta (date: 03/10/2024; Decision Number: 16; Protocol: 04/2024).

Research Design

A quasi-experimental pre-test–post-test control group design was used. Participants with chronic illnesses, musculoskeletal injuries, or those undergoing long-term medication were excluded from the study. To maintain physiological consistency during the intervention, participants and their parents were instructed to follow regular sleep and dietary routines. They were also advised to avoid cold or carbonated drinks, foods known to cause gastric discomfort, late-night activities, and intense physical activity outside the scheduled training.

The study was conducted at Sorowajan Sports Hall (GOR Sorowajan) in Yogyakarta. The intervention included 16 sessions. Training was held three times per week (Tuesday, Thursday, and Sunday). Each session lasted approximately 90 minutes.

Participants were withdrawn from the study if they developed conditions that could affect physical performance or interfere with physiological responses to training.

The Battle Shuttlecock model integrates specific skill training (lob technique) and aerobic development (VO_2max) into a single cooperative–competitive game structure. Table 1 presents a conceptual comparison between Battle Shuttlecock and established game-based pedagogical models.

The intervention in this study is structured as an educational game based on shuttlecocks and played on a badminton court. The default format is 4 vs 4. However, in practice, the number of players per team may vary (e.g., 3 vs 3 or 5 vs 5), depending on student availability, time constraints, and the need to ensure equal playing opportunities. These adjustments do not change the core structure of the game, as the rules, objectives, and activity flow remain consistent.

This game is not only a competitive physical activity. It also serves as a structured medium for motor, socio-affective, and cognitive learning. The objectives of the Battle Shuttlecock intervention include the integration of the following components:

- Physical – endurance, agility, aerobic capacity (VO_2max), hand-eye coordination.
- Technical – shuttlecock control, throwing accuracy, spatial awareness.
- Social-affective – cooperation, communication, sportsmanship, emotional regulation.
- Cognitive – quick decision-making, strategic planning, angle selection when throwing.

Game Phase. Court

The Battle Shuttlecock game is played on a modified badminton court, using standard dimensions with instructional adaptations. The court layout and setup are illustrated in Figure 1.

Using a standard badminton court (Figure 1)):

- Length: 13.40–13.60 m
- Width: 6.10 m

The outer boundary lines are used as the playing

Table 1. Conceptual comparison of Battle Shuttlecock with existing approaches

Comparison Aspect	Teaching Games for Understanding (TGfU)	Small-Sided Games (SSG)	Conventional Technical Training	Battle Shuttlecock
Main Objective	Tactical understanding	Increased playing intensity	Technical mastery	Integration of lob technique and VO_2max through gameplay
Pedagogical Focus	Tactical–cognitive	Physical activity	Technical–motor	Hybrid: technical, physical, tactical, social
Joyful Learning Aspect	High	High	Low	Very high (cooperative competition)
Specific Technical Integration	Not specific	Not focused	Highly focused	Integrated within gameplay
Activity Structure	Tactical modifications	Small-sided games	Drills	Mission-based team shuttlecock game
Biomotor Component	Minimal	Aerobic emphasis	Limited	Designed to improve VO_2max
Degree of Innovation	Established	Established	Traditional	New hybrid pedagogical model

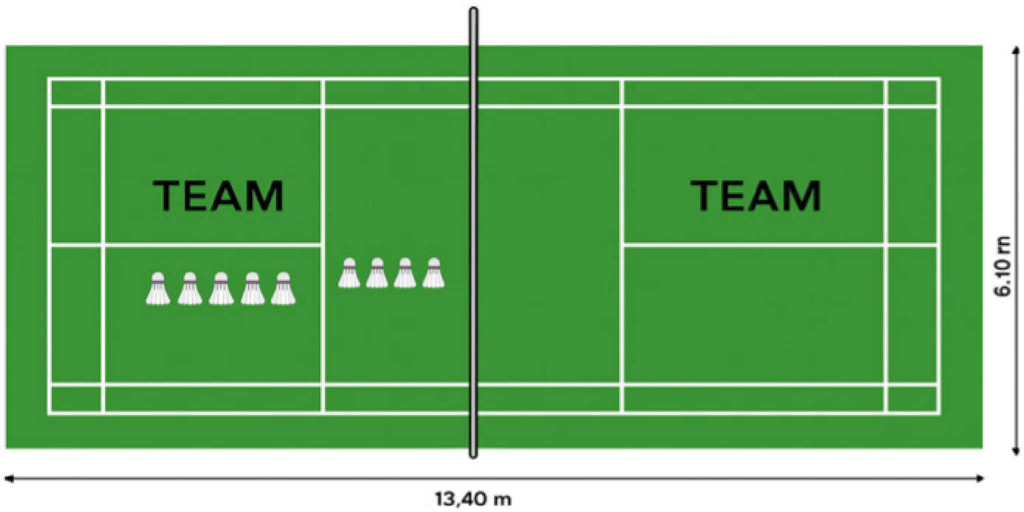

Figure 1. Battle Shuttlecock court

area limits.

The net is installed at the center of the court, with a height of 155 cm at the posts and 152.4 cm at the center, following standard badminton specifications.

Start Setup (Performed before each round).

Two teams face each other on opposite sides of the court, separated by a net.

The number of players is flexible (2–5 players per team) and may be adjusted depending on the number of students and the duration of the lesson.

Seven shuttlecocks are placed in one team's area to start the round.

Each shuttlecock must be thrown over the net into the opponent's area.

The round begins with a whistle or instruction and ends with another signal at a specified time limit.

Round Objective

Teams aim to keep their side of the court as clear as possible by the end of the round. The team with fewer shuttlecocks remaining in their area wins the round.

Rules of the Game

The Battle Shuttlecock game follows a set of structured rules to ensure consistency, safety, and educational value. These rules are summarized in Table 2.

Progressive Training Structure

The intervention consisted of 14 training sessions. This number was selected based on findings by Teixeira et al., which indicated that interventions with 14 to 16 sessions are effective in improving fitness and motor skills in children [24]. The structure and progression of the training sessions are outlined in Table 3.

Complete Procedure for Each Intervention Session

Each intervention session followed a structured sequence, consisting of four main phases: opening, warm-up, game play, and cool-down.

Opening Session:

- Attendance and readiness check.
- Prayer according to each participant's belief.
- Brief explanation of the session's objectives.

Warm-up:

Light jogging around the field (7 laps or approximately 5 minutes).

Dynamic stretching (10 minutes), including:

- Leg swings
- Arm circles
- Hip rotations.

Game Play (Main Session). The session began with a standard instructional script:

"Children, remember that the goal of the game is to keep our area clean of shuttlecocks. All shuttlecocks must be thrown over the net into the opponent's area. Use your dominant hand and throw

Table 2. Rules of the Battle Shuttlecock Game

Category	Specifications
Throw	The shuttlecock must pass over the net and land within the opponent's court. The target area is the deep zone of the opponent's court but must not cross the boundary lines. The throwing motion should resemble the lob technique in badminton, using correct stance and footwork.
Violations	Throwing the shuttlecock with the non-dominant (weak) hand. Throwing more than one shuttlecock at a time. Holding the shuttlecock for more than two seconds. Making intimidating gestures. Intentionally throwing the shuttlecock at an opponent's body.
Player Interaction	Players must throw the shuttlecock actively. Slow tossing or simply dropping the shuttlecock near the net is not allowed. Players must be ready to catch or retrieve shuttlecocks in their area. The game must remain dynamic and competitive.
Winner of the Round	The team with fewer shuttlecocks remaining in their area when time runs out.

Table 3. Progressive Training Structure

Session Phase	Games per Session	Game Duration	Rest Interval
Sessions 1–4	6 games	45 seconds	120 seconds
Sessions 5–9	7 games	45 seconds	100 seconds
Sessions 10–15	8 games	45 seconds	90 seconds
Session 16	Post-test	–	–

strongly, high, and far. Do not hold the shuttlecock for more than two seconds, and do not throw more than one at a time. Ready? We start when the whistle blows."

Round 1 procedure:

- The teacher or coach blows the whistle → the round begins.
- Players immediately throw shuttlecocks into the opponent's area as quickly and accurately as possible.
- The observer monitors and records any rule violations.
- After 45 seconds, the whistle is blown again → the round ends.
- Remaining shuttlecocks in each court area are counted → the winner is announced.

Number of rounds per session:

The number of rounds follows the progressive training structure (6–8 rounds per session).

Cool-down:

- Static stretching
- Deep breathing
- Muscle relaxation
- Closing prayer.

Intervention Fidelity Monitoring Elements

To ensure consistent implementation of the Battle Shuttlecock intervention, a structured checklist was used for session monitoring. The checklist covered key procedural and instructional elements. Table 4 presents the items used to monitor intervention fidelity.

Program Adaptation for Various Conditions

The Battle Shuttlecock program can be adapted to suit different class settings, facility limitations, and variations in student ability. The following adaptations are recommended:

Classes with Large Numbers of Students

To ensure fair and safe participation in large classes, the following adjustments can be made:

- Increase the number of players per team to a maximum of five.
- Use a rotation system between groups every 5–7 minutes to ensure all students participate.
- Create 1–2 additional courts using chalk lines or cones, allowing several groups to play in parallel.

Mixed-Gender Classes

To promote inclusive and balanced interaction between male and female students:

- Form teams with proportional representation of both genders.
- Provide a short briefing on sportsmanship, cooperation, and respectful communication before starting the game.

Limited Facilities and Infrastructure

If school facilities are incomplete, the following modifications can be implemented:

- If a net is unavailable, use a rope (e.g., raffia) and attach it to poles approximately 155 cm in height.
- If shuttlecocks are limited, use five shuttlecocks or replace them with foam balls.
- If there is no badminton court, draw a simple court using chalk.

Differences in Student Skill Levels

The program can be adapted to accommodate both beginners and more advanced students:

a. Beginners:

- Increase the number of players per team.
- Use more shuttlecocks.
- Reduce emphasis on lob shot technique; allow

Table 4. Intervention Implementation Monitoring Checklist

No.	Item Checklist	Yes	No	Notes
1	The court uses standard badminton dimensions and boundary lines.	☐	☐	
2	The number of shuttlecocks is as specified (7).	☐	☐	
3	Foul rules are enforced consistently.	☐	☐	
4	Each round lasts exactly 45 seconds (a timer is used).	☐	☐	
5	The number of rounds follows the session progression (6–8 rounds depending on phase).	☐	☐	
6	A complete warm-up is conducted (approximately 15 minutes).	☐	☐	
7	A complete cool-down is conducted (approximately 15 minutes).	☐	☐	
8	Initial instructions are delivered clearly before gameplay begins.	☐	☐	
9	Two coaches or teachers supervise each session.	☐	☐	
10	The winning team is determined objectively (based on remaining shuttlecocks).	☐	☐	
11	No rule modifications are made without the researcher's approval.	☐	☐	
12	All equipment (net, shuttlecocks, court lines, floor) is in safe condition.	☐	☐	
13	No player uses their non-dominant (weak) hand to throw.	☐	☐	
14	No player throws more than one shuttlecock at a time.	☐	☐	

basic throwing without requiring correct footwork.

- Allow free throwing based on ability, without focusing on accuracy or control.

b. Skilled Students:

- Reduce the number of players per team.
- Introduce narrow target zones using cones or markings to encourage precision.
- Emphasize lob technique with proper footwork, adapted from badminton throwing mechanics.

Instruments

1. Bleep Test (Multistage Fitness Test)

The Bleep Test is a practical and validated field method for measuring aerobic capacity (VO_2max). It is conducted as a 20-meter shuttle run with a progressively increasing pace. VO_2max is estimated based on the final level and number of shuttles completed [25]. Recent studies confirm the test's reliability in school-based physical education settings. Technological advancements—such as infrared sensors and automated VO_2max recording software—have improved the accuracy and ease of implementation [26, 27]. Comparative studies with rowing ergometers further support the Bleep Test as an efficient tool for assessing cardiorespiratory fitness in youth field environments [28].

2. French Clear Test (Test Pukulan Lob)

The French Clear Test is a standardized tool for assessing badminton lob skills. The test consists of 20 attempts, each scored for directional accuracy, height, and power using a zone-based system (3–5–4–2–1). Additional scoring criteria include zero points for missed shots, counting the boundary lines as part of the higher-value zone, and disqualifying attempts that fail to clear an 8-foot tape positioned 14 feet from the net.

The test demonstrates strong reliability (0.96) and moderate validity (0.60) [29]. It functions not only as an objective assessment tool but also as a pedagogical resource in elementary physical education. It supports structured and measurable learning of fundamental badminton techniques in alignment with sport pedagogy principles. The test layout and scoring zones are illustrated in Figure 2.

3. Battle Shuttlecock Game Intervention Evaluation Instrument

a. Perceived Competence (Illustrated). This instrument assesses students' perceived competence in motor activities. It includes indicators such as confidence in performing motor skills, ability to follow instructions, and perceived success in completing tasks. A pictorial format was selected to enhance comprehension among elementary school students. This approach is supported by findings from Morano et al., who demonstrated the effectiveness of visual response formats for measuring self-efficacy in children [31].

Measurement category: Psychological aspects – self-perception / self-efficacy. Scoring Interpretation:

- 3–5: Low – limited confidence and perceived ability in motor tasks
- 6–7: Moderate – adequate ability with partial confidence
- 8–9: High – strong self-confidence, ability, and task competence.

b. Mini-PACES (Physical Activity Enjoyment Scale – Short Version)

Mini-PACES is used to assess students' enjoyment while playing Battle Shuttlecock. It includes four indicators: pleasure, interest, perceived excitement, and willingness to participate again. The scale has demonstrated validity and reliability for use with children [32, 33].

Measurement category: Affective domain – enjoyment.

Assessment rules: Responses are rated on a 1–5 Likert scale (total score range: 4–20).

Scoring Interpretation:

- 16–20: High – strong enjoyment and engagement
- 12–15: Moderate – moderate enjoyment
- <12: Low – limited enjoyment or engagement.

***C.** Fidelity Checklist*

The fidelity checklist is used to ensure that the Battle Shuttlecock intervention is implemented in accordance with the established protocol. It evaluates key aspects such as rule consistency, number of rounds, session duration, warm-up and

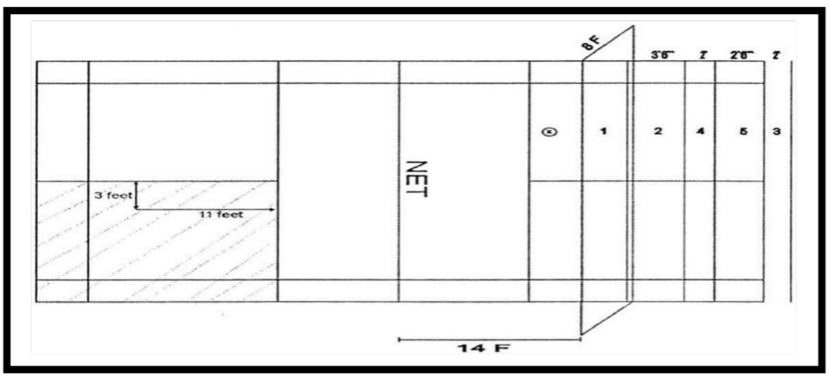

Figure 2. French Clear Test (Badminton Lob Skill Test) [30]

cool-down implementation, facility safety, clarity of instructions, availability of equipment, and teacher supervision.

A high level of implementation fidelity is essential for the accurate interpretation of outcomes and for consistent program replication. It also strengthens the validity of findings by ensuring that the intervention is delivered as intended [34, 35].

Measurement category: Treatment fidelity / implementation integrity.

Assessment method: Dichotomous scale (0 = not implemented, 1 = implemented). Scoring Interpretation:

- High: 85% or more of items fulfilled
- Moderate: 70–84%
- Low: less than 70%.

d. Observation Sheet (Social–Affective & Cognitive)

This observation sheet is used to assess student behavior during gameplay across two domains: social–affective and cognitive. Three observers independently rate each student, and the average score is calculated to enhance inter-rater reliability in accordance with physical education research standards.

Measurement category: Behavioral observation – social, affective, and cognitive domains. Scoring Interpretation:

Social–Affective Domain:

- 4–7: Low – limited cooperation, weak emotional regulation, inconsistent sportsmanship
- 8–10: Moderate – adequate cooperation and sportsmanship, but unstable
- 11–12: High – strong cooperation, communication, emotional control, and sportsmanship

Cognitive Domain:

- 4–6: Low – limited rule understanding and decision-making
- 7–8: Moderate – basic rule comprehension and emerging decision-making, but inconsistent
- 9–12: High – good understanding of rules, strategic thinking, and adaptability

Statistical Analysis

All data were analyzed using SPSS version 26. To assess the effect of the Battle Shuttlecock intervention on VO_2max and lob performance, a Multivariate Analysis of Variance (MANOVA) was conducted. This procedure was used to compare differences between the experimental and control groups across both dependent variables simultaneously. Prior to analysis, the assumption of normality was tested using the Shapiro–Wilk test, and homogeneity of variance was assessed using Levene's test. The significance level was set at $\alpha = 0.05$. When MANOVA results indicated a significant effect ($p < 0.05$), follow-up independent t-tests were performed for each dependent variable to identify specific group differences.

Results

Descriptive results for VO_2max and lob stroke performance in the experimental and control groups are presented in Table 5. Values are reported as means, standard deviations (SD), and 95% confidence intervals (CI). In the experimental group, both VO_2max and lob stroke performance showed improvement from pre-test to post-test. The increase in VO_2max was modest, while the improvement in lob stroke accuracy was more pronounced. In contrast, the control group showed minimal change in VO_2max and only a small gain in lob performance, suggesting a greater overall effect in the experimental condition.

Descriptive results and score distribution for perceived competence are shown in Table 6. The data include the minimum and maximum scores, score range, mean, median, mode, and the distribution of total scores based on the number of students. The distribution shows that most students reported

Table 5. Descriptive statistics of VO_2max and lob stroke performance

Variable	Group	Pre-test Mean ± SD (95% CI)	Post-test Mean ± SD (95% CI)
VO_2max	Experimental	38.5 ± 2.9 (37.0–40.0)	39.1 ± 2.6 (37.8–40.5)
	Control	38.8 ± 3.0 (37.2–40.4)	38.6 ± 2.8 (37.2–40.0)
Lob stroke	Experimental	55.3 ± 6.7 (51.7–59.0)	64.2 ± 7.1 (60.3–68.1)
	Control	67.4 ± 5.9 (64.2–70.7)	70.1 ± 6.0 (66.8–73.4)

Table 6. Descriptive statistics and distribution of perceived competence scores

Descriptive Statistics	Scores	Distribution of Total Scores (3–9)	Number of Students
Minimum Score	6	6	1
Maximum Score	9	7	3
Score Range	6–9	8	7
Average (Mean)	8.06	9	5
Median	8	–	–
Mode	8 and 9	–	–

moderate to high perceived competence scores. The most frequent scores were 8 and 9, indicating strong self-confidence in motor performance among participants. The minimum score observed was 6, with only one student falling into the lower confidence category.

The distribution of Mini-PACES scores and corresponding interpretations of student enjoyment are presented in Table 7. The results are categorized by score level, number of students, percentage, and interpretation. Most students reported high to very high levels of enjoyment during the Battle Shuttlecock activity. Notably, 8 out of 16 students (50.1%) reached the top two scores (19–20), indicating a strong positive affective response. No students fell into the low enjoyment category, suggesting that the game was well-received by the majority of participants.

Descriptive data from structured observations illustrating the average social–affective and cognitive scores for individual students are presented in Table 8. Scores are classified into low, medium, or high categories according to predetermined rubrics. Observation results indicate that all students demonstrated at least a medium level of both social–affective and cognitive performance. Two students reached high cognitive scores, while one student achieved a high social–affective score. No low scores were recorded, suggesting generally positive behavioral and cognitive engagement during the intervention.

Descriptive data from the Fidelity Checklist, used to evaluate the consistency of implementation across intervention sessions, are presented in Table 9. Fidelity was calculated as the proportion of checklist items fulfilled during each session. Fidelity scores ranged from 0.58 to 0.75, with most sessions meeting over 75% of implementation criteria. Sessions 7, 11, and 13 showed slightly lower fidelity, indicating minor deviations from protocol. Overall, the intervention was implemented with a consistently high level of procedural adherence.

Assumption testing confirmed the suitability of parametric analyses. The Shapiro–Wilk test indicated that all variables were normally distributed ($p > 0.05$). Levene's test confirmed homogeneity of variances across groups ($p > 0.05$). These results are summarized in Table 10, which presents the paired t-test outcomes for VO_2max and lob stroke performance before and after the intervention.

The results indicated a significant change over time within the full sample on both outcome variables.

An independent t-test was conducted to compare performance between groups. Table 11 shows the between-group differences for VO_2max and lob

Table 7. Distribution of Mini-PACES scores and interpretations of student enjoyment

Score	Number of Students	Percentage	Interpretation
20	1	6.3%	Very high enjoyment
19	7	43.8%	Very high enjoyment
18	1	6.3%	High enjoyment
17	4	25.0%	High enjoyment
16	1	6.3%	Moderate enjoyment
15	2	12.5%	Moderate enjoyment

Table 8. Descriptive observations of social–affective and cognitive skills

No	Student	Social–Affective Score	Category	Cognitive Score	Category
1	A	12	High	7	Medium
2	B	10	Medium	7	Medium
3	C	11	Medium	9	High
4	D	10	Medium	8	High

Table 9. Fidelity checklist results across 14 intervention sessions

Session	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Fidelity Score	0.75	0.75	0.75	0.75	0.75	0.75	0.67	0.75	0.75	0.75	0.58	0.75	0.67	0.75

Table 10. Paired t-test results of VO_2max and lob stroke

Pair	Mean Difference	SD	t	df	p-value
VO_2max (pre–post)	−0.62	0.70	−4.96	31	<0.001
Lob stroke (pre–post)	−8.94	7.69	−6.58	31	<0.001

Table 11. Independent t-test results between groups

Variable	Time	t	df	p-value	Mean Difference (95% CI)
VO_2max	pre	−1.03	30	0.309	−0.34 (−1.00; 0.33)
VO_2max	post	1.05	30	0.302	0.44 (−0.42; 1.31)
Lob stroke	pre	2.94	30	0.006	12.06 (3.67; 20.46)
Lob stroke	post	3.57	30	0.001	16.56 (7.08; 26.04)

Table 12. MANCOVA results for post-test VO_2max and lob stroke (covarying pre-test)

Dependent Variable	Source	F	df	p-value	Partial η^2
VO_2max_post	Group	20.003	1,28	<0.001	0.417
VO_2max_post	VO_2max_pre	107.110	1,28	<0.001	0.793
Lob_post	Group	3.972	1,28	0.056	0.124
Lob_post	Lob_pre	59.293	1,28	<0.001	0.679

stroke at both pre-test and post-test phases.

The groups showed no significant differences in VO_2max. However, lob stroke performance differed significantly between the groups at both time points.

To assess the impact of the intervention while controlling for baseline values, a multivariate analysis of covariance (MANCOVA) was conducted. Table 12 summarizes the adjusted outcomes for post-test VO_2max and lob stroke performance, controlling for respective pre-test values.

The group factor had a significant effect on post-test VO_2max after adjusting for baseline scores. For lob stroke, the effect approached significance, suggesting a positive trend favoring the intervention group.

Discussion

This study aimed to examine the effects of the Battle Shuttlecock game on VO_2max and lob shot performance in elementary school students. It also evaluated the pedagogical relevance of this intervention within the context of school-based physical education.

The term "Battle Shuttlecock" reflects terminology commonly used in coaching and teaching practice. It refers to structured activities that are both competitive and focused on skill development. Similar expressions such as "Shuttle Battle" or "Cone Wars" are frequently used to combine movement tasks with playful language. This helps increase student engagement and improves communication during instruction. Although the term is not formally defined in academic literature, it is consistent with school-based game design practices and supports the model's accessibility and clarity for educators.

The results showed that students in the experimental group improved both aerobic capacity and lob shot performance. The control group, which received conventional badminton training, did not achieve significant gains in VO_2max and showed only a modest improvement in lob performance. These findings suggest that integrating technical and aerobic training into a structured game format can lead to simultaneous development of physical fitness and motor skills. The outcomes support the use of hybrid pedagogical models in physical education for improving both physiological and technical competencies in children.

Findings from this study align with theoretical frameworks that support integrated and experiential learning models. The Battle Shuttlecock game simultaneously incorporates skill training (lob technique) and aerobic stimulation (VO_2max) within a cooperative-competitive structure. This approach extends existing models such as TGfU by embedding physical and sport-specific technical demands into the game design, demonstrating that game-based pedagogy can function beyond tactical understanding alone [20].

In addition, the model reflects core principles of physical literacy. It combines movement competence, confidence, and motivation with sport-specific execution and active engagement, thereby reinforcing a holistic view of student development [21]. These features correspond to the concept of embodied pedagogy, where students develop understanding through physical experience and reflection during gameplay [22].

Furthermore, the instructional design of Battle Shuttlecock encourages teachers to integrate content, learning strategies, and gameplay, creating conditions for meaningful and developmentally appropriate physical education, particularly for children [23]. The use of cooperative-competitive formats and mission-based tasks may also enhance intrinsic motivation, active participation, and social interaction, expanding the pedagogical value of such interventions beyond isolated performance metrics.

Previous studies have shown that extracurricular sports programs in elementary schools contribute to improvements in physical fitness, motor skills, and students' character development. School-based physical activity interventions have consistently been associated with enhanced fitness, increased activity levels, and better socio-emotional development in children [1, 2]. Seefeldt's concept of proficiency barriers highlights that mastering fundamental motor skills is a prerequisite for the acquisition of more complex sport-specific abilities. This concept has been supported by recent longitudinal studies [3].

In this context, badminton serves as both a recreational and competitive sport that develops coordination, agility, endurance, and concentration [4]. The lob shot is a fundamental technique that involves a high and deep shuttlecock trajectory, allowing players to recover position and disrupt their opponent's strategy [8]. Mastery of the lob shot depends on physical conditioning, particularly aerobic capacity (VO_2max), due to the intense and rally-based nature of the game [6]. At the same time, multiple reports indicate a decline in children's cardiorespiratory fitness in recent decades, emphasizing the need for early intervention at the elementary school level [7].

The findings of this study demonstrate that the shuttlecock throwing game program had a positive effect on VO_2max and lob shot performance in the experimental group. VO_2max increased from 38.5 ± 2.9 to 39.1 ± 2.6 ml/kg/min, while lob shot scores improved from 55.3 ± 6.7 to 64.2 ± 7.1 points. In contrast, the control group showed minimal changes. Paired t-tests confirmed statistically significant increases in both variables ($p < 0.001$). The MANCOVA results also supported the simultaneous effect of the intervention on aerobic capacity and technical performance. From a physiological perspective, these outcomes are consistent with previous studies showing that games involving fast, repetitive, and controlled movements can improve VO_2max and cardiorespiratory endurance [36, 37, 38, 39, 40]. Additional research has indicated that game-based training and competitive circuit formats are effective in enhancing aerobic capacity in young badminton players [41]. A recent meta-analysis further confirms that high-intensity and sprint interval training consistently benefits VO_2max in badminton athletes [42].

Beyond physiological improvements, the observed increase in lob performance indicates that game-based learning can effectively enhance technical skill execution. This finding aligns with previous research suggesting that engaging and competitive learning environments support skill development [43, 44]. Recent studies have shown that game-based methods in physical education improve student engagement, motivation, and the transfer of skills to real play situations [12, 42, 45]. The framework of Meaningful Physical Education emphasizes that relevance, challenge, and enjoyment are key factors in increasing student participation and learning outcomes [10, 11]. Similar benefits have been observed in other racket sports, such as tennis and squash, where game-based approaches improve both technical skills and physical conditioning [46].

These quantitative outcomes are supported by descriptive data on student perceptions and behavior. Perceived competence scores ranged from 6 to 9, with a mean of 8.06. This indicates that most students felt capable of participating effectively. According to Self-Determination Theory, perceived competence is a key factor influencing intrinsic motivation [47]. Enjoyment data showed that most students fell into the high or very high categories. This suggests that the shuttlecock games offered a positive and motivating learning experience. Recent research highlights that enjoyment is an important predictor of continued physical activity in children [19]. Observational data also revealed consistent social–affective and cognitive engagement. This finding is in line with studies showing that game-based learning supports social interaction, problem-solving, and tactical understanding [48]. Additionally, fidelity scores between 0.58 and 0.75 reflect stable implementation of the intervention. This consistency helps ensure that the observed outcomes can be attributed to the actual learning activities provided [34].

Practically, these findings provide useful guidance for physical education teachers and beginner coaches. Shuttlecock-based games can be used as an effective instructional approach to improve both aerobic fitness and lob shot technique. This is relevant because aerobic fitness supports sustained performance during rallies, while the lob shot is a core skill at all levels of badminton play [49]. Compared to traditional technique-focused drills, game-based learning shows better outcomes in both fitness and skill development [12, 45]. Studies in futsal and soccer also show that small-sided game formats can improve both VO_2max and technical execution [50, 51]. These results support the integration of physical and technical elements into structured and meaningful game contexts.

Limitations of the Study

This study has several limitations that should be considered when interpreting the results. First, the sample was small and drawn from one elementary school. This limits the generalizability of the findings to other populations with different cultural backgrounds or badminton experience. Second, the intervention was short in duration, and no follow-up was conducted. Therefore, the long-term effects on VO_2max and lob-shot performance remain unknown. Third, although objective data on VO_2max and lob technique were collected, psychological factors such as motivation, engagement, and enjoyment were not systematically assessed. These variables may influence learning outcomes. Fourth, confounding factors such as nutrition, physical activity outside of school, and teaching quality were not controlled and may have affected the results. Finally, this study did not compare Battle Shuttlecock with other game-based pedagogical models. As a result, conclusions about its relative effectiveness remain limited.

Future studies should include larger samples from multiple schools to improve external validity and allow broader generalization. Longitudinal research is needed to assess whether improvements in aerobic capacity and lob-shot performance are sustained over time. Future work should also incorporate validated measures of motivation, engagement, and enjoyment. These psychological factors are important for understanding learning outcomes. In addition, researchers should control for potential confounders such as nutritional status, extracurricular physical activity, and differences in teaching quality. Comparative studies are recommended to evaluate the effectiveness of Battle Shuttlecock relative to other game-based pedagogical models.

Conclusions

The Battle Shuttlecock game offers a structured approach to combining technical skill practice and aerobic activity within physical education settings. Its design supports cooperation, engagement, and alignment with general educational principles. The model may be suitable for lessons that aim to address both physical and pedagogical goals in a balanced manner. By incorporating elements of skill development and physical exertion into a game format, this approach can contribute to diversified learning experiences in school-based physical education.

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Conflict of Interest

The author declares no potential conflict of interest, financial or non-financial, related to the conduct of this research or the preparation of this article.

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ORIGINAL ARTICLE

Increasing maximum angular velocity of the jab punch in amateur boxers

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Abstract

Background and Study Aim The jab punch represents a fundamental technical element in boxing and relies on coordinated interaction of multiple body segments. Effective execution of this technique depends on the sequential involvement of the shoulder, elbow, pelvis, hip, knee, and ankle joints, which collectively contribute to punch speed and force generation. Despite the application of various training approaches aimed at improving punching performance, their relative effectiveness in modifying joint angular velocity during jab execution remains of practical interest. The aim was to quantify joint angular velocity during jab execution using 3D biomechanical analysis and to assess changes following targeted training.

Material and Methods The study was conducted using a three-dimensional motion capture system with twelve synchronized cameras. Twenty-four amateur male boxers (age 19 ± 2.1 years, height 172 ± 6.9 cm, body mass 69 ± 6.83 kg) were randomly assigned to an experimental group and a control group. To develop joint angular velocity and improve segmental coordination during jab execution, the experimental group completed a four-week targeted training program comprising ten structured exercises, while the control group followed a conventional training routine. Training load and exercise intensity were monitored using a Polar H10 heart rate sensor. Kinematic data were processed using Motive software to calculate joint angular velocity parameters.

Results The experimental group demonstrated significant increases in angular velocity at the shoulder joints, including left shoulder flexion and extension (from 512.5 ± 44.73 to 573.82 ± 68.2°/s, $p < 0.05$), as well as at the elbow joints, with left elbow angular velocity increasing from 439.4 ± 37.78 to 472.24 ± 39.11°/s ($p < 0.05$). Pelvic rotational velocity showed a pronounced increase from 153.8 ± 18.22 to 269.45 ± 33.78°/s ($p < 0.001$). Positive changes were also observed in the hip joints, particularly left hip flexion and extension (from 67.6 ± 8.62 to 89.01 ± 8.08°/s, $p < 0.001$), and in the ankle joints, with left ankle angular velocity increasing from 63.23 ± 8.32 to 68.24 ± 5.44°/s ($p < 0.001$), indicating improved kinetic chain coordination. No statistically significant changes were found in the control group.

Conclusions The specialized training program resulted in short-term improvements in jab punch mechanics. Increased angular velocity enhanced the contribution of both upper and lower body segments, leading to faster and more forceful punch execution. The findings emphasize the importance of lower-body involvement and provide practical guidance for boxing training programs.

Keywords: angular velocity, boxing, biomechanical analysis, striking technique, body alignment, technical exercises

Introduction

Punch speed and efficiency are components of boxing performance, particularly in actions used to initiate or control tactical exchanges. The jab punch involves coordinated movement of multiple body segments, in which force generation depends on the transfer of motion through the kinetic chain rather than on isolated upper-limb action. Joint angular velocity influences punch speed and mechanical execution, as it reflects the timing and sequencing of segmental movements. From this perspective, analysis of joint-specific contributions provides a basis for examining biomechanical characteristics of the jab punch and their modification through structured training interventions.

Biomechanical characteristics of punching movements in boxing have been examined with emphasis on the structural organization of straight punches and the interaction of body segments. Kinematic analyses have shown that effective punch execution involves coordinated motion of the shoulder, elbow, and wrist, rather than isolated upper-limb action [1, 2]. These studies describe punching as a structured movement

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pattern governed by joint sequencing and temporal coordination.

Subsequent investigations extended this approach to whole-body mechanics, demonstrating that lower-limb and pelvic actions contribute to force generation and transmission during straight punches [3, 4]. The involvement of the trunk and legs forms a continuous kinetic chain that supports upper-limb acceleration and punch delivery.

Variations in biomechanical parameters have been reported across different skill levels. Analyses of straight right-hand punches indicate differences in joint kinematics and execution patterns between boxers of varying qualifications, while preserving common structural features of the movement [5, 6]. These findings collectively characterize punching in boxing as a complex, multi-segmental motor action.

Segmental coordination is a defining feature of effective striking actions in combat sports. Biomechanical studies describe punching movements as sequences in which motion is transferred from proximal to distal segments, allowing mechanical energy to be accumulated and released through the kinetic chain [3, 7]. This sequencing supports the development of higher end-point velocities while maintaining movement control.

Research focusing on intermuscular and intersegmental coordination indicates that punch execution depends on precise temporal alignment of lower- and upper-body segments. Investigations of straight punches in boxing highlight the role of coordinated activation of the legs, trunk, and upper limbs in stabilizing movement patterns and regulating angular velocity across joints [2, 8, 9].

Comparative kinematic analyses of different punching strategies further demonstrate that variations in sequencing affect joint angular velocity and overall punch mechanics. Studies comparing proximal-to-distal and simultaneous movement patterns report differences in pelvic, shoulder, and elbow coordination, influencing the efficiency of force transfer during straight punches [10].

Angular velocity is a central kinematic parameter used to describe the mechanical execution of straight punches. Analyses of boxing punches have shown that joint angular velocity reflects the timing and coordination of segmental movements, particularly at the shoulder and elbow joints [1, 2]. Differences in angular velocity profiles have been reported between punch types, indicating distinct movement strategies within straight and rotational techniques.

Further studies have examined angular velocity in relation to technical variation and athlete qualification. Investigations of straight right-hand punches demonstrate that joint kinematics, including angular velocity and joint angles, vary according to execution patterns while preserving common structural features of the movement [3, 5]. These variations influence the mechanical characteristics of punch delivery.

Comparative kinematic analyses of different sequencing strategies reveal that proximal-to-distal coordination affects peak angular velocity and its distribution across joints. Distinct patterns of pelvic, shoulder, and elbow rotation have been associated with differences in punch mechanics and movement efficiency [10].

Lower-limb and pelvic mechanics play a substantial role in the execution of striking movements across combat sports. Kinematic studies indicate that effective strikes rely on coordinated actions of the pelvis, hip, knee, and ankle joints, which contribute to the generation and transfer of mechanical energy toward the striking segment [7, 9, 11]. The involvement of these segments supports the acceleration of the distal limbs during punch and kick execution.

Research on kicking techniques in taekwondo and karate provides additional insight into the influence of lower-body mechanics on striking performance. Analyses of turning, back, and roundhouse kicks show that strike velocity depends on leg positioning, joint angular velocity, and the timing of pelvic rotation [12, 13, 14]. Similar relationships have been observed in studies examining the effects of wearable resistance and joint kinematics on lower-limb strike velocity and force production [15].

Variations in attack angle and movement amplitude have also been shown to affect lower-limb kinematics. Changes in pelvic rotation, knee flexion, and limb trajectory influence both strike velocity and execution time, highlighting the need for coordinated lower-body control during striking actions [16].

Temporal characteristics are an integral component of punching performance in boxing. Analyses of punch execution have shown that parameters such as movement duration, active phase time, and return time to the initial position influence the overall structure and effectiveness of striking actions [6, 17]. These temporal features reflect the coordination between preparatory and execution phases of the punch.

Reaction time has been examined in relation to different punch types and skill levels. Comparative assessments indicate that faster reaction responses are associated with more efficient execution of offensive and defensive punching actions, including rapid transitions between attack and counterattack [18]. Together, these findings underline the role of temporal regulation in the organization of boxing punches.

Methodological approaches to teaching punching techniques are commonly based on biomechanical models of movement execution. Studies focusing on the instruction of basic punches describe the use of structured motor models that emphasize sequential learning and controlled progression of technical elements [19]. Such approaches aim to standardize movement patterns and support the development of stable punching techniques.

Pedagogical analyses also highlight the role of coordination training in technical instruction. Research on intermuscular coordination during straight punches indicates that targeted exercises and regulated external loads influence movement stability and the timing of muscle activation, which is relevant for technical refinement in boxing training [8]. Biomechanical comparisons of different punch execution strategies further contribute to instructional design by identifying movement characteristics associated with coordinated joint action and sequential movement organization [10]. In addition, analyses of biomechanical and physical factors related to performance in amateur boxing emphasize the contribution of coordinated interaction between the lower limbs, shoulder girdle, and arm muscles to punch effectiveness [20].

Analysis of research findings has shown that punching techniques in boxing are based on coordinated interaction of multiple body segments, with angular velocity and temporal sequencing influencing strike execution. Researchers emphasize that effective punch performance depends on the integration of upper- and lower-body mechanics and on the regulation of joint-specific kinematic parameters under dynamic conditions. At the same time, the complexity of these interactions and their modification through structured training interventions continue to present methodological challenges in applied biomechanics. In this context, the aim was to measure angular velocity during jab execution using three-dimensional biomechanical analysis and to evaluate improvements after targeted training.

Materials and Methods

Participants

Twenty-four healthy athletes without musculoskeletal injuries participated in the study. All participants were students of the Uzbek State University of Physical Education and Sports. They were randomly assigned to an experimental group (EG) and a control group (CG). Participation was voluntary, and all athletes provided informed consent prior to data collection. The study protocol was approved by the Ethics Committee of the Uzbek State University of Physical Education and Sports, and all procedures were conducted in accordance with institutional ethical standards.

Study Design

Punching movements were recorded using the STT Full Body Analysis system, which enables synchronized three-dimensional tracking of whole-body motion. The motion-capture setup consisted of Q13 fixed optoelectronic cameras mounted on wall or ceiling fixtures and FFY cameras installed on tripods around the capture area to ensure adequate coverage of dynamic body segments. Q13 cameras were connected to the network via Ethernet, while FFY cameras were linked to the workstation using USB 3.1 interfaces. All devices were operated through 3DMA Full Body software, which controlled system calibration, data acquisition, and three-dimensional reconstruction of joint kinematics.

Before testing, a standard calibration procedure was performed to ensure spatial accuracy and synchronization across all cameras. Kinematic data included three-dimensional positions and joint angles of the shoulder, elbow, pelvis, hip, knee, ankle, and foot in the sagittal, coronal, and transverse planes. Motion analysis focused on punching actions, allowing assessment of joint coordination and movement efficiency during jab execution. Angular velocity and acceleration parameters were calculated to characterize punch mechanics and segmental interaction.

As part of the training intervention, a structured set of physical exercises was included to regulate training load and to support the development of general and boxing-specific physical qualities. Exercise intensity was monitored using heart rate responses and basic workload parameters. The intervention comprised ten exercises targeting strength, coordination, endurance, and segmental interaction relevant to jab execution, with detailed load characteristics summarized in Table 1:

1. *Jumping rope* was used as a general conditioning exercise aimed at developing endurance, balance, and foot speed. Heart rate increased from 111 bpm at rest to 158–180 bpm during exercise and decreased to 110–120 bpm during recovery. The exercise duration was 12–14 min, repeated 3–4 times, with an estimated energy expenditure of approximately 150 kcal and a total distance of about 610 m. The exercise was performed in an upright posture with continuous rope rotation, slight knee flexion, and minimal ground contact during landing.
2. *Pull-ups on a horizontal bar* were performed to develop upper-body strength and static–dynamic endurance. Heart rate increased from 115 bpm before exercise to 162–175 bpm during execution and decreased to 120–130 bpm during recovery. The protocol consisted of 2–4 sets with a total duration of 15–20 min and an estimated energy expenditure of approximately 150 kcal. The exercise was executed using a wide or shoulder-width grip, with controlled vertical movement and maintenance of a straight body alignment throughout the action.
3. *Medicine ball slams* were included to develop explosive strength and coordination. Heart rate

increased from 129 bpm at rest to 169–176 bpm during exercise and decreased to 110–120 bpm during recovery. The exercise was performed in 2–4 sets with a total duration of 12–14 min and an estimated energy expenditure of approximately 170 kcal. The movement involved coordinated throwing and rotational actions, requiring synchronized activation of the upper limbs and trunk to support whole-body coordination relevant to punching mechanics.

4. *Kettlebell swings* were used to develop explosive strength and general physical endurance. Heart rate increased from 129 bpm before exercise to 170–176 bpm during execution and decreased to 110–120 bpm during recovery. The protocol consisted of 2–4 sets with a total duration of 15–20 min and an estimated energy expenditure of approximately 150 kcal. The exercise was performed with controlled sagittal-plane movement and trunk rotation while maintaining an upright posture, engaging the lower limbs, trunk, and shoulder girdle to support balance and coordinated force production during punching actions.
5. *Squat exercises* were used to develop lower-limb strength, explosive power, and balance. Heart rate increased from 117 bpm before exercise to 160–173 bpm during execution and decreased to 110–120 bpm during recovery. The exercise was performed in 2–4 sets with a total duration of 10–12 min and an estimated energy expenditure of approximately 90 kcal. Squats were executed with knee flexion to approximately 90° and controlled trunk positioning, engaging the lower limbs and core to support movement stability and force production relevant to boxing actions.
6. *Barbell rotational strikes* were used to develop rotational strength and coordinated striking actions. Heart rate increased from 121 bpm before exercise to 168–172 bpm during execution and decreased to 110–120 bpm during recovery. The protocol consisted of 2–4 sets with a total duration of 15–20 min and an estimated energy expenditure of approximately 195 kcal. The exercise involved trunk rotation with unilateral external resistance, engaging the abdominal and back musculature to support force generation and coordination during punching movements.
7. *Sledgehammer tire slams* were applied to develop upper-body strength and explosive movement patterns. Heart rate increased from 117 bpm before exercise to 171–180 bpm during execution and decreased to 110–120 bpm during recovery. The exercise was performed in 2–4 sets with a total duration of 15–20 min and an estimated energy expenditure of approximately 245 kcal. The movement involved repeated overhead striking actions with external resistance, requiring coordinated activation of the upper limbs and trunk to support force transmission during punching movements.
8. *Agility ladder drills* were used to develop foot speed, balance, and coordination. Heart rate increased from 119 bpm before exercise to 161–169 bpm during execution and decreased to 110–120 bpm during recovery. The exercise was performed in 2–3 sets with a total duration of 12–14 min and an estimated energy expenditure of approximately 105 kcal. The drills involved rapid multidirectional foot movements along predefined patterns, requiring precise lower-limb coordination to support movement control during boxing actions.
9. *Push-up exercises* were included to develop upper-body strength and muscular endurance. The exercise engaged the chest, shoulder, arm, and trunk muscles and was performed with controlled movement while maintaining a straight body alignment to support upper-body stabilization relevant to punching actions.
10. *Floor-based speed bag punching* was applied to develop upper-body muscular endurance and coordination. Heart rate increased from 119 bpm before exercise to 149–152 bpm during execution and decreased to 110–120 bpm during recovery. The protocol consisted of 2–4 sets with a total duration of 15–20 min and an estimated energy expenditure of approximately 120 kcal. The exercise involved rhythmic, high-frequency punching movements performed with controlled upper-limb coordination to support muscular endurance during punching actions.

To summarize the structure, intensity, and physiological characteristics of the training intervention, the parameters of the complex exercise set used to increase joint angular velocity during jab execution are presented in Table 1.

To classify training load intensity based on heart rate responses recorded during the exercises, heart rate zones used for workout intensity differentiation are presented in Table 2.

Statistical Analysis

Three-dimensional kinematic variables were obtained using Motive software and processed for statistical evaluation. Data are presented as mean values with standard deviations. Comparative analysis was performed to assess differences between the experimental and control groups, as well as changes in joint angular velocity before and after the training intervention. Statistical significance of differences was determined using parametric comparison procedures, with p-values reported for each analyzed variable. Coefficients of variation were calculated to evaluate the consistency of movement execution. Statistical analysis was applied to identify changes in joint angular velocity

Table 1. Complex exercise set used to increase joint angular velocity during jab execution in boxers

No.	Exercise	Heart rate before workout (bpm)	Heart rate during workout (bpm)	Heart rate after workout (bpm)	Rest time between sets (s)	Repetitions per set	Exercise duration per set (min)	Estimated energy expenditure (kcal)	Estimated distance (m)
1	Jump rope	89 ± 9.3	158 ± 14.7	110–120	110–120	3–4	12–14	150 ± 10	–
2	Pull-ups	85 ± 8.1	153 ± 12.5	110–120	110–120	2–4	15–20	150 ± 11	–
3	Medicine ball slams	91 ± 9.5	169 ± 15.2	110–120	110–120	2–4	12–14	170 ± 12	145 ± 14
4	Kettlebell swings	93 ± 8.8	170 ± 16.0	110–120	110–120	2–4	15–20	150 ± 13	60 ± 8
5	Squats	87 ± 7.9	159 ± 13.8	110–120	110–120	2–4	10–12	90 ± 9	20 ± 5
6	Barbell rotational strikes	92 ± 9.0	168 ± 15.1	110–120	110–120	2–4	15–20	195 ± 14	70 ± 9
7	Sledgehammer tire slams	96 ± 8.7	171 ± 17.3	110–120	110–120	2–4	15–20	245 ± 18	55 ± 7
8	Agility ladder drills	88 ± 8.5	156 ± 12.4	110–120	110–120	2–3	12–14	105 ± 9	250 ± 20
9	Push-ups	91 ± 8.3	149 ± 11.9	110–120	110–120	2–4	15–20	120 ± 8	–
10	Speed bag punches	79 ± 8.9	157 ± 13.4	110–120	110–120	2–3	12–14	105 ± 10	225 ± 18

Table 2. Heart rate intensity zones used to categorize training load during workouts

No.	Intensity zone	Heart rate range (bpm)
1	Very low intensity	89–119
2	Low intensity	120–139
3	Moderate intensity	140–159
4	High intensity	160–179
5	Very high intensity	180–200

and intersegmental coordination associated with the training program.

Results

Specialized training led to an increase in the angular velocity of the jab punch at several joints, including the shoulder, pelvis, hip, and elbow, in the experimental group. Changes in angular velocity were associated with modifications in movement coordination and segmental interaction within the kinetic chain. In contrast, the control group demonstrated only minor changes in these parameters, indicating limited adaptation under standard training conditions.

Baseline kinematic characteristics of maximum joint angular velocity during jab execution in the control group before the experiment are presented in Figure 1. The data illustrate the distribution of angular velocity across upper- and lower-body joints during punch execution.

Kinematic assessment of the control group's jab technique before the intervention, as shown in Figure 1, demonstrated that maximum angular velocities were observed at the left shoulder (522.6°/s), left elbow (441.4°/s), and left ankle (61.17°/s). These values indicate that the jab was executed with the left arm, with the shoulder and elbow joints contributing primarily to punch speed generation. Low coefficients of variation (V% < 12%) across most joints suggest a relatively consistent technical execution among participants. Lower-extremity joints, including the hip, knee, and ankle, also contributed to jab execution but showed slightly greater variability (V% = 11–13%), indicating less stable coordination in these segments. Overall, jab execution followed a sequential pattern involving the left shoulder, elbow, and pelvic rotation, supporting momentum transfer along the kinetic chain.

Kinematic indicators of maximum joint angular velocity during jab execution in the experimental group before the intervention are presented in Figure 2.

Kinematic assessment of the experimental group's jab technique before the intervention, as shown in Figure 2, demonstrated peak angular

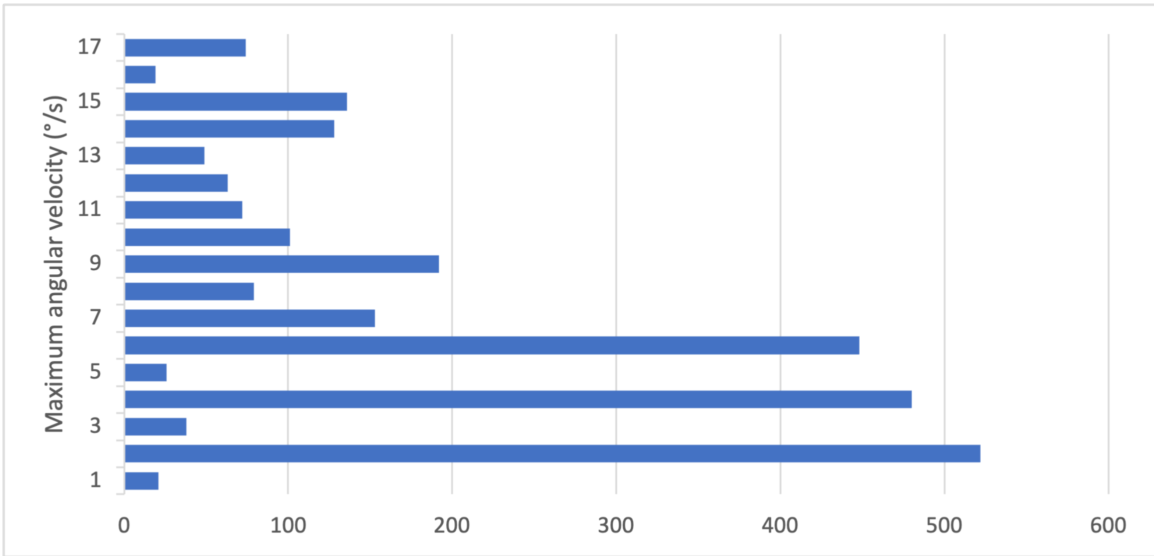

Figure 1. Kinematic indicators of the maximum angular velocity of body joints during jab technique execution in control group boxers before the experiment (n = 12). Note: 1 – right shoulder flexion/extension; 2 – left shoulder flexion/extension; 3 – right shoulder flexion/extension (vertical movement); 4 – left shoulder flexion/extension (vertical movement); 5 – right elbow flexion/extension; 6 – left elbow flexion/extension; 7 – pelvis rotation; 8 – pelvis rotation (right segment); 9 – pelvis rotation (left segment); 10 – right hip flexion/extension; 11 – left hip flexion/extension; 12 – right hip abduction/adduction; 13 – left hip abduction/adduction; 14 – right knee flexion/extension; 15 – left knee flexion/extension; 16 – right ankle flexion/extension; 17 – left ankle flexion/extension.

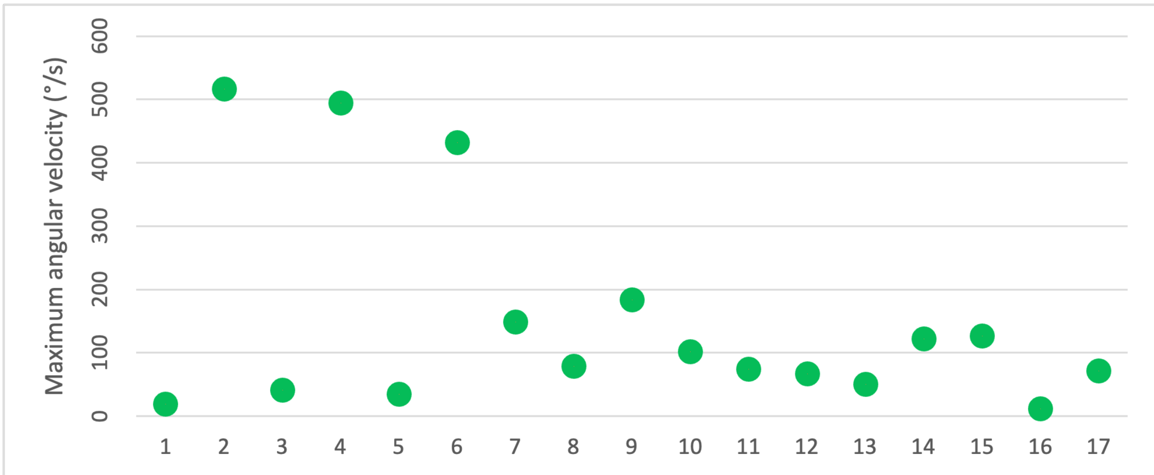

Figure 2. Kinematic indicators of the maximum angular velocity of body joints during jab technique execution in experimental group boxers before the experiment (n = 12). Note: 1 – right shoulder flexion/extension; 2 – left shoulder flexion/extension; 3 – right shoulder flexion/extension (vertical movement); 4 – left shoulder flexion/extension (vertical movement); 5 – right elbow flexion/extension; 6 – left elbow flexion/extension; 7 – pelvis rotation; 8 – pelvis rotation (right segment); 9 – pelvis rotation (left segment); 10 – right hip flexion/extension; 11 – left hip flexion/extension; 12 – right hip abduction/adduction; 13 – left hip abduction/adduction; 14 – right knee flexion/extension; 15 – left knee flexion/extension; 16 – right ankle flexion/extension; 17 – left ankle flexion/extension.

velocities at the left shoulder (512.5°/s), left elbow (439.4°/s), and left ankle (63.23°/s). These values indicate left-arm execution of the jab, with the shoulder and elbow joints contributing substantially to punch velocity. Low coefficients of variation in these joints (V% ≈ 8–9%) suggest relatively consistent movement patterns across participants. Lower-extremity joints, including the hip, knee, and ankle, exhibited higher variability (V% = 11–15%), indicating less stable coordination in these segments. Overall, jab execution was characterized by a biomechanical sequence involving the left shoulder, elbow, and hip, reflecting integrated participation of upper and lower body segments.

Comparative kinematic indicators of maximum joint angular velocity for the experimental and control groups are summarized in Table 3.

As shown in Table 3, the analysis of maximum shoulder angular velocity during jab execution demonstrated statistically significant improvements in the experimental group compared with the control group. Significant increases were observed in both

Table 3. Kinematic indicators of the maximum angular velocity of body joints during jab execution in experimental and control groups (n = 24)

Parameters	Stage	CG (mean ± SD)	V%	EG (mean ± SD)	V%	t	P
Shoulders							
Right shoulder flexion/extension	BE	23.63 ± 2.40	10.16	24.68 ± 3.21	13.01	1.74	>0.05
	AE	31.14 ± 3.51	11.27	38.67 ± 3.10	8.02	3.14	<0.001
Left shoulder flexion/extension	BE	522.6 ± 44.73	8.56	512.5 ± 44.73	8.73	10.21	>0.05
	AE	534.6 ± 52.41	9.80	573.82 ± 68.20	11.89	2.25	<0.05
Right shoulder flexion/extension (vertical)	BE	34.8 ± 4.05	11.64	34.3 ± 5.11	14.90	0.77	>0.05
	AE	42.4 ± 5.12	12.08	48.21 ± 3.49	7.24	3.16	<0.001
Left shoulder flexion/extension (vertical)	BE	490.9 ± 42.51	8.66	495.9 ± 42.51	8.91	0.15	>0.05
	AE	540.4 ± 54.24	10.04	614.17 ± 64.14	10.44	2.37	<0.05
Elbows							
Right elbow flexion/extension	BE	25.3 ± 2.14	8.46	26.4 ± 2.97	11.25	1.14	>0.05
	AE	31.3 ± 2.14	6.84	35.26 ± 3.68	10.44	2.23	<0.05
Left elbow flexion/extension	BE	441.4 ± 54.14	7.73	439.4 ± 37.78	8.60	0.87	>0.05
	AE	452.3 ± 52.24	11.54	472.24 ± 39.11	8.28	2.34	<0.05
Pelvis							
Pelvis rotation	BE	156.8 ± 16.22	10.34	153.8 ± 18.22	11.85	0.81	>0.05
	AE	208.4 ± 25.97	12.46	269.45 ± 33.78	12.54	5.63	<0.001
Pelvis rotation (right)	BE	71.25 ± 8.20	11.51	74.77 ± 9.21	12.31	1.41	>0.05
	AE	81.3 ± 9.97	12.26	87.88 ± 8.93	10.16	2.25	<0.05
Pelvis rotation (left)	BE	182.4 ± 20.60	11.29	176.3 ± 17.65	10.01	1.24	>0.05
	AE	225.3 ± 32.97	14.63	299.07 ± 33.34	11.15	6.68	<0.001
Hips							
Right hip flexion/extension	BE	102.2 ± 10.52	10.29	104.2 ± 12.20	11.71	0.92	>0.05
	AE	108.3 ± 12.97	2.74	112.47 ± 11.32	10.06	2.25	<0.05
Left hip flexion/extension	BE	65.6 ± 5.77	8.80	67.6 ± 8.62	8.31	0.74	>0.05
	AE	74.3 ± 9.97	13.41	89.01 ± 8.08	9.08	4.23	<0.001
Right hip abduction/adduction	BE	46.2 ± 5.89	12.75	48.45 ± 7.65	15.79	1.23	>0.05
	AE	47.2 ± 5.97	12.64	53.66 ± 6.43	11.98	2.25	<0.05
Left hip abduction/adduction	BE	35.06 ± 3.90	11.12	37.0 ± 4.25	11.48	1.04	>0.05
	AE	41.4 ± 5.97	14.42	47.75 ± 5.54	11.60	4.37	<0.001
Knees							
Right knee flexion/extension	BE	127.75 ± 13.80	10.80	128.14 ± 14.21	11.09	0.37	>0.05
	AE	121.3 ± 17.97	14.81	116.31 ± 11.43	9.83	2.63	<0.05
Left knee flexion/extension	BE	135.8 ± 15.80	11.63	132.12 ± 14.21	10.76	0.74	>0.05
	AE	138.3 ± 17.97	12.95	142.72 ± 11.74	8.23	2.58	<0.005
Ankles							
Right ankle flexion/extension	BE	12.70 ± 1.65	12.99	13.41 ± 1.84	13.72	0.87	>0.05
	AE	14.4 ± 1.85	12.85	15.20 ± 1.88	12.37	2.31	<0.05
Left ankle flexion/extension	BE	61.17 ± 7.21	11.79	63.23 ± 8.32	13.16	0.74	>0.05
	AE	54.4 ± 8.97	16.49	68.24 ± 5.44	7.79	3.23	<0.001

Note: BE – before experiment; AE – after experiment; CG – control group; EG – experimental group.

right and left shoulder flexion/extension movements, including vertical components ($p < 0.05$ to $p < 0.001$). In contrast, the control group exhibited minimal or non-significant changes. A similar pattern was observed for elbow joint kinematics. The experimental group demonstrated significant increases in maximum angular velocity in both right and left elbow flexion/extension after the intervention ($p < 0.05$), whereas no statistically significant changes were detected in the control group.

Kinematic indicators of maximum joint angular velocity during jab execution in the control group after the experiment are presented in Figure 3. Figure 3 provides a visual representation of post-intervention joint angular velocity patterns in the control group.

As shown in Table 3, the experimental group demonstrated a substantial improvement in pelvic rotation during jab execution, particularly in total and left segment rotation. Specifically, total pelvic rotation increased from 153.8 to 269.45 ($p < 0.001$), while left segment rotation increased from 176.3 to 299.07 ($p < 0.001$). The right segment rotation also exhibited a statistically significant increase ($p < 0.05$). In contrast, the control group showed only modest and statistically non-significant changes. Significant improvements were also observed in hip joint angular velocity in the experimental group. Increases were most pronounced in left hip flexion/extension (from 67.6 to 89.01, $p < 0.001$) and left hip abduction/adduction (from 37 to 47.75, $p < 0.001$). Additional statistically significant changes were found in right hip flexion and right hip abduction (both $p < 0.05$). No statistically significant changes were observed in the control group.

As illustrated in Figure 4, the experimental group demonstrated statistically significant changes in knee joint angular velocity during jab execution for both lower limbs. The right knee showed a decrease in angular velocity from 128.14 to 116.31 ($p < 0.05$), indicating altered movement control during punch delivery. In contrast, the left knee exhibited an increase from 132.12 to 142.72 ($p < 0.005$), reflecting changes in movement contribution of the supporting leg. No statistically significant changes were observed in the control group. Significant changes were also observed in ankle joint angular velocity in the experimental group, as shown in Figure 4. The right ankle demonstrated an increase from 13.41 to 15.20 ($p < 0.05$), while the left ankle showed a more pronounced increase from 63.23 to 68.24 ($p < 0.001$). The control group did not exhibit statistically significant changes in ankle joint angular velocity. These results indicate modifications in lower-limb kinematic behavior associated with the training intervention.

Relationships between joint angular velocity parameters in the experimental group after the intervention are summarized in Table 4.

As shown in Table 4, strong inter-joint correlations ($r \geq 0.7$) were identified when the maximum angular velocity of body joints during jab execution was analyzed in the experimental group after the experiment. Specifically, right pelvis rotation correlated with right shoulder flexion/extension ($r = 0.8$), left ankle flexion/extension correlated with right shoulder flexion/extension ($r = 0.7$), left hip flexion/extension correlated with both

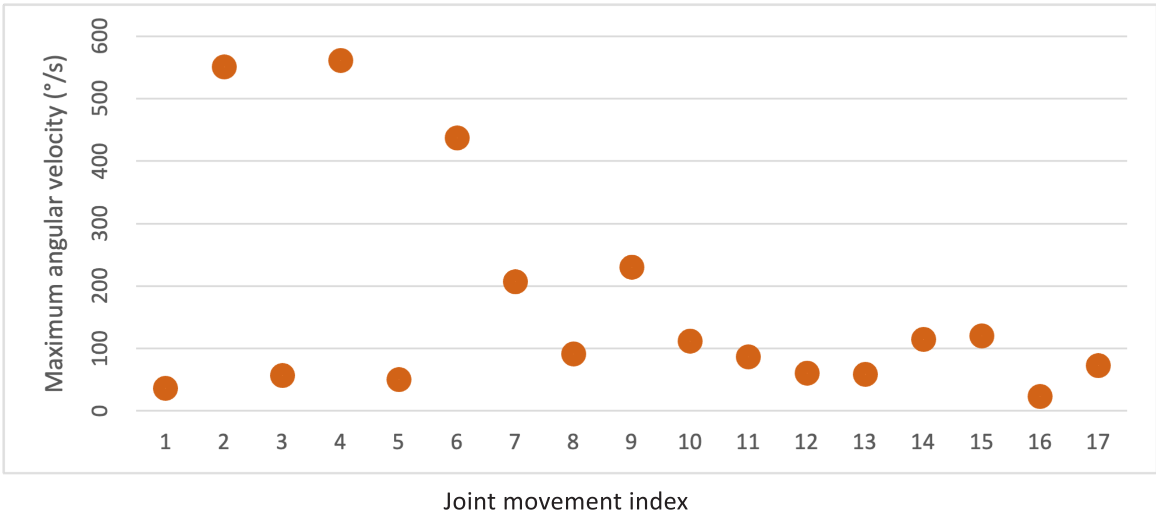

Figure 3. Kinematic indicators of the maximum angular velocity of body joints during jab technique execution in control group boxers after the experiment (n = 12). Note: 1 – right shoulder flexion/extension; 2 – left shoulder flexion/extension; 3 – right shoulder flexion/extension (vertical movement); 4 – left shoulder flexion/extension (vertical movement); 5 – right elbow flexion/extension; 6 – left elbow flexion/extension; 7 – pelvis rotation; 8 – pelvis rotation (right segment); 9 – pelvis rotation (left segment); 10 – right hip flexion/extension; 11 – left hip flexion/extension; 12 – right hip abduction/adduction; 13 – left hip abduction/adduction; 14 – right knee flexion/extension; 15 – left knee flexion/extension; 16 – right ankle flexion/extension; 17 – left ankle flexion/extension.

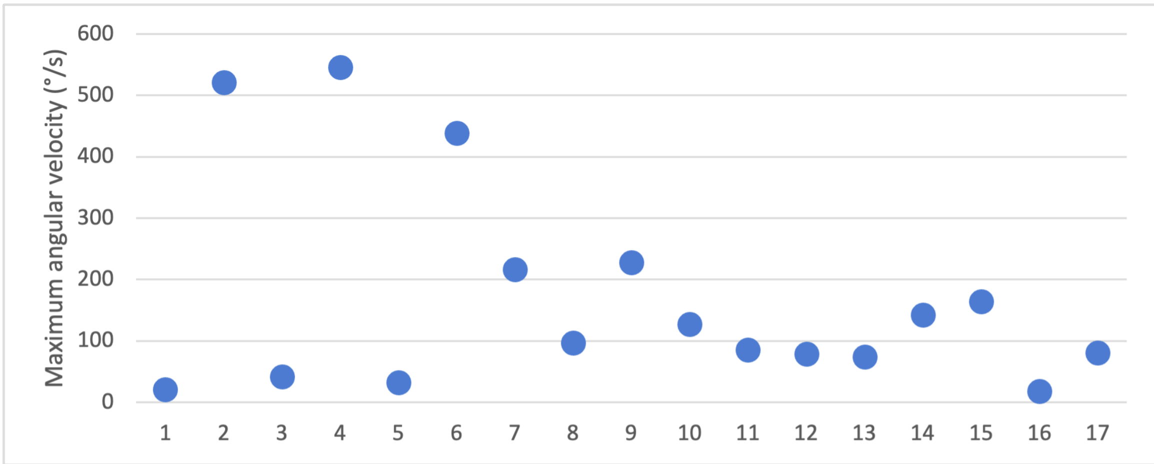

Figure 4. Kinematic indicators of the maximum angular velocity of body joints during jab technique execution in experimental group boxers after the experiment (n = 12). Note: 1 – right shoulder flexion/extension; 2 – left shoulder flexion/extension; 3 – right shoulder flexion/extension (vertical movement); 4 – left shoulder flexion/extension (vertical movement); 5 – right elbow flexion/extension; 6 – left elbow flexion/extension; 7 – pelvis rotation; 8 – pelvis rotation (right segment); 9 – pelvis rotation (left segment); 10 – right hip flexion/extension; 11 – left hip flexion/extension; 12 – right hip abduction/adduction; 13 – left hip abduction/adduction; 14 – right knee flexion/extension; 15 – left knee flexion/extension; 16 – right ankle flexion/extension; 17 – left ankle flexion/extension.

Table 4. Correlation of maximum angular velocity kinematics of body joints during jab execution in experimental group boxers after the experiment (n = 12)

№	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0.3																
2	0.6																
3	0.4	0.3															
4	0.3	0	0.3														
5	0.5	0.3	0.1	0.7													
6	0.3	0.2	0.4	0.4	0.3												
7	0.6	0.5	0.8	0.3	0.1	0.6											
8	0.8	0.7	0.3	0.3	0.6	0.2	0.4										
9	0.6	0.2	0.5	0.2	0.3	0.5	0.6	0.4									
10	0.4	0.2	0.2	0.4	0.3	0.2	0.2	0.1	0.7								
11	0.6	0.1	0.2	0.5	0.5	0.2	0.3	0.4	0.7	0.7							
12	0.6	0.2	0.6	0	0.2	0.5	0.7	0.4	0.8	0.6	0.6						
13	0.2	0.2	0	0.3	0.1	0.3	0.1	0	0.6	0.7	0.7	0.5					
14	0.5	0.5	0.5	0.2	0.6	0.1	0.4	0.5	0.2	0	0.2	0.3	0.2				
15	0.6	0.5	0.6	0.2	0.6	0	0.5	0.6	0.4	0.2	0.3	0.4	0.1	0.8			
16	0.5	0.1	0.1	0.7	0.6	0	0.1	0.4	0.5	0.6	0.7	0.4	0.6	0.1	0.2		
17	0.7	0.4	0.7	0.7	0.3	0.4	0.8	0.5	0.7	0.4	0.5	0.7	0.2	0.6	0.6	0.3	0.5

Note: 1 – right shoulder flexion/extension; 2 – left shoulder flexion/extension; 3 – right shoulder flexion/extension (vertical movement); 4 – left shoulder flexion/extension (vertical movement); 5 – right elbow flexion/extension; 6 – left elbow flexion/extension; 7 – pelvis rotation; 8 – pelvis rotation (right segment); 9 – pelvis rotation (left segment); 10 – right hip flexion/extension; 11 – left hip flexion/extension; 12 – right hip abduction/adduction; 13 – left hip abduction/adduction; 14 – right knee flexion/extension; 15 – left knee flexion/extension; 16 – right ankle flexion/extension; 17 – left ankle flexion/extension. Correlation coefficients are presented as Pearson's r.

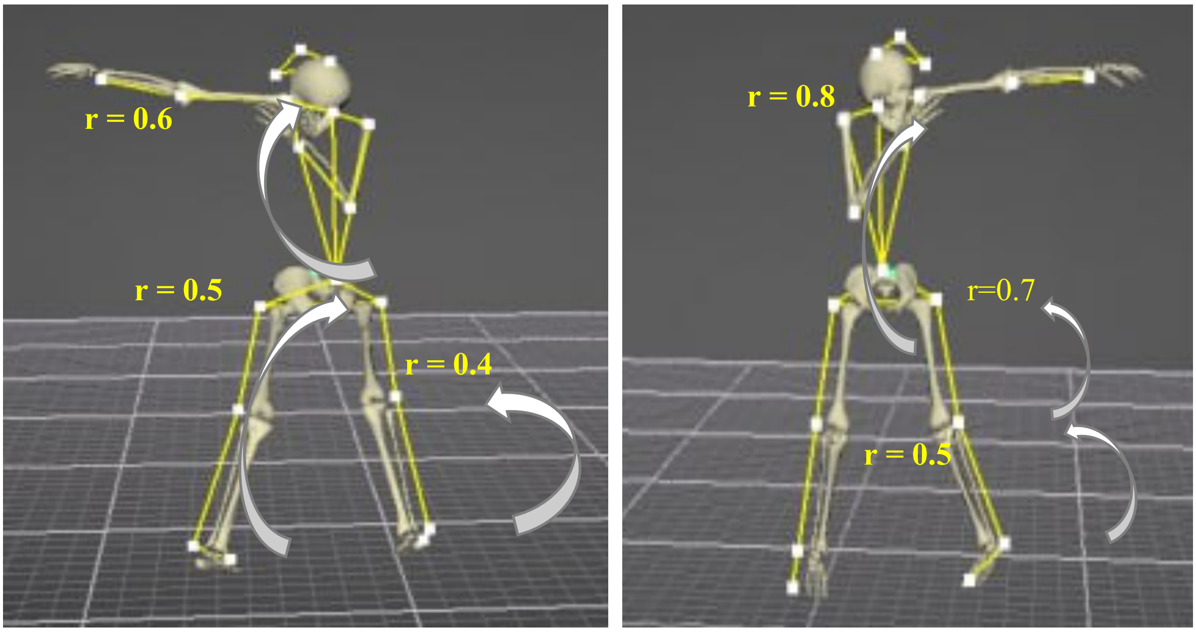

Figure 5. Correlation of body joint movements during the execution of a jab by boxers. Note: Correlation coefficients represent Pearson's r calculated between the maximum angular velocity values of body joints during jab execution in the experimental group after the experiment (n = 12).

right hip flexion/extension and pelvis rotation (r = 0.7), and right hip abduction/adduction correlated with left pelvis rotation (r = 0.8). These relationships indicate coordinated interaction between the upper and lower limbs and the pelvis during jab execution. Weak or negligible correlations (r < 0.4) were also observed for several joint movements in the experimental group. In particular, left shoulder flexion/extension in the vertical plane and left elbow flexion/extension demonstrated low correlation coefficients, suggesting a more supportive role of these joints during punch execution.

A graphical representation of the correlation structure between body joint movements during jab execution is presented in Figure 5.

As illustrated in Figure 5, post-experiment kinematic analysis of jab execution in the experimental group revealed interdependence among joint movements across multiple body segments. The strongest relationships were observed between the pelvis, hip joints, shoulder girdle, and ankle joints, indicating coordinated involvement of these segments during jab execution. The observed pattern reflects sequential interaction along the kinetic chain, with motion transferred from the lower extremities toward the upper body. Moderate correlations were also identified among several joint movements, suggesting partial coordination between these segments during the punch. In particular, joints on the non-dominant side demonstrated lower correlation values, indicating a more limited contribution to the overall movement pattern. These findings highlight variability in segmental involvement during jab execution and illustrate differences between primary and supportive joint actions.

Discussion

The aim was to quantify joint angular velocity during jab execution using 3D biomechanical analysis and to assess changes following targeted training. The results showed that the applied training intervention was associated with increased angular velocity in several upper- and lower-body joints, including the shoulder, elbow, pelvis, hip, and ankle, in the experimental group, while no comparable changes were observed in the control group. These findings indicate that modifications in segmental motion characteristics occurred alongside the training program, providing a basis for further interpretation of joint coordination and kinetic chain involvement during jab execution.

The observed increase in ankle joint angular velocity during jab execution in the experimental group can be discussed in the context of both earlier and recent biomechanical research. Previous studies have reported that modifications in lower-limb kinematics, including ankle joint motion, are associated with changes in movement coordination and force transmission during punching actions [2, 6, 7, 10]. These findings support the interpretation that alterations at the ankle level reflect adjustments in lower-limb involvement within the kinetic chain during jab execution.

Recent biomechanical investigations further reinforce this perspective. Studies employing synchronized three-dimensional motion capture and force platform analysis have demonstrated that lower-extremity force development and foot–ground interaction variables are related to straight-punch kinematics and punching speed, highlighting the contribution of distal lower-limb segments to effective punch execution [21]. In addition, contemporary research has shown that lower-limb kinetic variables remain relevant across different punch types, including the jab, and may be influenced by fatigue, indicating that changes in ankle joint behavior can affect overall biomechanical efficiency during striking movements [22]. Phase-based analyses based on ground reaction force timing also indicate that lower-body involvement precedes and supports upper-limb motion, which is consistent with the view that ankle joint kinematics contribute to segmental coordination during jab execution [23].

The observed changes support the concept that punching movements are executed through a kinetic chain involving force transmission from proximal to distal segments [10]. This interpretation is consistent with recent research showing that lower-limb kinetic variables (including ground reaction force and rate of force development) contribute to punch output across common punch types, including the jab, indicating that lower-body mechanics form part of the force–velocity pathway during striking actions [23]. Evidence from studies examining boxing-specific fatigue further indicates that perturbations to lower-body and trunk function can modify punching performance, supporting the view that whole-body sequencing is relevant to punch execution mechanics [24]. In addition, recent work examining jab and cross performance through whole-body mechanical models (e.g., effective mass and force-transfer characteristics) reinforces that punch effectiveness depends on coordinated segmental contribution rather than isolated upper-limb action [25]. Within this framework, ankle joint motion plays a role in initiating and supporting the mechanical sequence of jab execution, providing a distal component for force transmission through the kinetic chain [1, 8].

The importance of lower-extremity stability and coordinated joint action in punching performance is supported by both earlier and recent biomechanical research. Stanley and colleagues reported that coordinated movements of the lower limbs contribute to changes in punch force generation [6, 20]. The absence of comparable changes in the control group in the present study suggests that the observed kinematic modifications are associated with the applied targeted training approach rather than general training effects [9].

Contemporary evidence further highlights relationships between lower-limb stability, muscle strength, and dynamic control with striking performance. A recent investigation assessing hip strength, foot posture, and dynamic stability in boxers found significant correlations between hip strength and lower-limb dynamic stability, suggesting that stronger lower-limb musculature and improved balance contribute to more stable and effective movement patterns relevant to upper-body actions [26]. Another study reported that dynamic balance measures were significant predictors of punching performance, with better balance associated with faster and more powerful strikes, indicating that stability of the lower limbs is linked to global striking mechanics [27]. Additionally, research using force plates and biomechanical analysis demonstrated that lower-limb force generation and rate of force development contribute to punch effectiveness and fatigue resilience, underscoring the role of lower-limb kinetics in coordinated whole-body performance [23].

Earlier investigations indicated that non-specific physical training may not lead to measurable changes in joint kinematics during punching movements [2]. The current findings are consistent with these observations and support the use of targeted exercises aimed at modifying specific joint motion characteristics in order to achieve detectable biomechanical changes. Recent studies comparing variable resistance training and constant resistance training within complex training programs in elite boxers reported different adaptation patterns, with training modalities that were closely aligned with boxing movements producing greater improvements in strength and punch-related performance measures than general conditioning approaches [28]. A four-week contrast training intervention in amateur boxers also demonstrated that structured strength and power oriented programs resulted in more pronounced enhancements in punch force and physical performance compared with traditional conditioning, suggesting that training specificity influences neuromuscular adaptations relevant to striking actions [29]. In addition, investigations of boxing specific conditioning tasks such as punch related dumbbell exercises reported acute improvements in punch performance when compared with less specific preparatory activities, indicating that conditioning methods closely matched to the movement task can induce measurable performance effects [30].

The present findings are consistent with biomechanical models that emphasize coordinated integration of upper- and lower-body segments during jab execution. Earlier work demonstrated that lower-limb stability and initial force generation contribute to effective upper-limb motion during punching actions, supporting the concept of whole-body involvement in strike production [1]. Similarly, the intersegmental kinetic transfer model proposes that power and velocity generated by the lower-limb segments influence upper-body movement characteristics during striking tasks [7].

Recent investigations further support this framework. A biomechanical analysis of lead straight punches in boxers of different performance levels demonstrated that coordination between lower-limb force production and upper-limb kinematics is associated with higher punching velocity and mechanical efficiency, highlighting the role of segmental integration across the body [21]. In addition, whole-body modeling of jab and cross punches showed that effective mass and force transmission depend on synchronized contributions of the lower extremities, trunk, and upper limbs rather than isolated arm action [25]. Contemporary studies examining lower-limb kinetics and ground reaction force timing also reported that force generation in the lower body precedes and supports upper-limb acceleration during punching movements, reinforcing the relevance of integrated segmental coordination [23]. Within this context, observed changes in ankle joint motion may reflect adjustments in the lower-body contribution to the overall kinetic sequence of jab execution.

Limitations and Future Research

Several limitations of the present study should be acknowledged. First, the sample size was relatively small and consisted of amateur boxers of a similar age and training background, which may limit the generalizability of the findings to athletes of different competitive levels, age groups, or training histories. Second, the duration of the intervention was limited to a short training period, which does not allow conclusions to be drawn regarding long-term adaptations or retention of the observed kinematic changes. Third, the analysis focused primarily on kinematic parameters derived from three-dimensional motion capture, while kinetic variables such as ground reaction forces and muscle activation patterns were not directly assessed. As a result, interpretations regarding force generation and neuromuscular mechanisms remain indirect.

Future research should consider larger and more diverse samples, including boxers of different skill levels and competitive experience, to further examine the generalizability of the findings. Longitudinal study designs would allow investigation of long-term adaptations to targeted training interventions and their influence on punching mechanics over time. In addition, the integration of kinetic measurements, electromyography, and fatigue-related protocols may provide a more comprehensive understanding of the mechanisms underlying changes in joint angular velocity and segmental coordination during jab execution. Further studies may also explore the transfer of biomechanical changes to competitive performance indicators and injury risk in boxing.

Conclusions

This study addresses biomechanical aspects of jab execution in amateur boxing with an emphasis on joint angular velocity and segmental coordination. The findings highlight the relevance of movement organization based on proximal-to-distal sequencing and coordinated involvement of lower- and upper-body segments in boxing technique. From an applied perspective, the study supports the integration of kinematically oriented lower-body exercises into boxing training programs as a means of refining technical execution and movement efficiency. The conclusions may be useful for coaches, sports scientists, and rehabilitation specialists when designing training and corrective interventions aimed at improving movement quality and technical consistency in boxing.

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Conflict of Interest

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

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ORIGINAL ARTICLE

Long-interval training effects on VO_2max, resting heart rate, and body composition in Pencak Silat athletes aged 16–18 years

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Abstract

Background and Study Aim Aerobic capacity, cardiac efficiency, and metabolic regulation contribute directly to performance in Pencak Silat. The sport involves intermittent high-intensity actions that place continuous demands on cardiovascular and metabolic systems. Although various conditioning approaches are used in practice, their relative effectiveness in improving responses relevant to Pencak Silat remains a matter of practical interest. This study aimed to evaluate how a structured long-interval training program influences aerobic capacity, heart rate regulation, and body composition indicators in Pencak Silat athletes aged 16–18 years.

Material and Methods A quasi-experimental pretest–posttest design with a comparison group was used. Twenty athletes aged 16–18 years were assigned either to an LIT group or to a control group that continued regular training. Aerobic capacity (VO_2max) was measured with the Multi-Fitness Test (MFT). Resting heart rate, body fat, and visceral fat were assessed using a bioelectrical impedance device. Because the data were not normally distributed, non-parametric tests were applied.

Results The LIT program significantly improved VO_2max ($p = 0.001$) and reduced RHR ($p = 0.001$) compared with the control group. Total and visceral fat also decreased significantly in the LIT group ($p = 0.001$), although the reduction in body fat between groups remained modest. These changes indicate combined cardiovascular and metabolic adaptations in response to long-interval training. The results are consistent with the demands of Pencak Silat, where higher aerobic efficiency and lower central fat support movement economy and technical execution.

Conclusions The study indicates that long-interval training can be used as a structured approach to modify aerobic, cardiac, and body composition indicators in trained youth. The findings support the use of interval-based programs in sports with intermittent high-intensity efforts. They may help practitioners choose conditioning methods that match these demands.

Keywords: aerobic performance, cardiovascular adaptation, autonomic regulation, metabolic indicators, interval-based conditioning, visceral adiposity

Introduction

Physical performance in Pencak Silat depends on the interaction between aerobic capacity, heart rate responses, and body composition. The sport involves repeated high-intensity actions that create sustained demands on cardiovascular and metabolic systems. These demands make the regulation of aerobic work, recovery capacity, and central fat distribution an important part of preparation for young athletes. Structured interval-based training is often used to address these requirements because it provides controlled and repeatable physiological stimuli.

These demands highlight the importance of the physiological factors that support sustained work and recovery in combat sports. Athletic performance in Pencak Silat depends not only on technical execution but also on aerobic capacity and body composition [1]. Aerobic capacity and body composition, including visceral fat, influence endurance, energy use, and overall functional readiness in young athletes. Aerobic capacity, commonly assessed through VO_2max, reflects the efficiency of oxygen delivery during intensive activity [2]. Visceral fat affects physical performance and metabolic status because it is hormonally active and associated with insulin resistance and inflammatory processes [3].

In Pencak Silat, athletes work under varying movement intensities, demanding exchanges,

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and short recovery periods, which increase the importance of aerobic capacity and metabolic efficiency [4]. These features require high aerobic power and effective energy use. The training response in athletes aged 16–18 years is also shaped by ongoing growth, which can influence how they adapt to high-intensity programs, including interval training [5]. Studies in martial arts and related sports have reported that interval training can raise VO_2max and affect body fat, but its specific effects on visceral fat in this age group are examined infrequently [6]. Many available studies also focus on general or obese youth populations rather than trained adolescents, which limits sport-specific conclusions.

Beyond aerobic capacity and body composition, heart rate (HR) is a common indicator used in exercise science. HR monitoring offers a simple, non-invasive way to observe cardiovascular strain, exercise intensity, and recovery patterns [7]. In applied sport settings, HR data help estimate training load and guide adjustments to planned sessions [8]. Heart rate variability (HRV), defined as the beat-to-beat fluctuation in HR, is also used to assess autonomic regulation and recovery status [9, 10]. Interpretation of HR during high-intensity or interval training requires caution, because delayed cardiovascular responses and irregular recovery periods can limit its accuracy as a proxy for metabolic load [11]. HR and HRV values therefore need to be interpreted in relation to the structure of the session, recovery duration, and the athlete's fitness level [7].

Long-interval training (LIT) involves high-intensity exercise performed over intervals of two to four minutes with planned recovery periods [12]. Studies comparing high-intensity interval training (HIIT) with continuous exercise report similar effects on body fat, while HIIT often produces greater changes in VO_2max or metabolic efficiency [13]. In contrast with short-interval or sprint protocols, LIT provides a steadier aerobic stimulus and enables athletes to spend more time near VO_2max. It also supports central cardiovascular adaptations and reflects the intermittent yet sustained effort patterns seen in Pencak Silat. Interval training, including long-interval formats, can reduce total and visceral fat and contribute to favorable body-composition profiles, although the size of these changes varies with the duration and volume of the training program [14, 15].

Analysis of research findings has shown that interval-based methods can influence aerobic capacity, heart rate responses, and body-composition indicators in young athletes. Authors emphasize that the effects of these methods depend on the structure of the training load and on the physiological demands of sports with intermittent high-intensity actions. Researchers also note that adaptations during late adolescence may differ from those observed in adults, which adds complexity to training design. Together, these considerations highlight the relevance of examining how structured long-interval formats operate under conditions comparable to those encountered in Pencak Silat and create the basis for defining the specific focus of the present study.

These observations also draw attention to how interval-based methods may function in sports with distinct movement structures and recovery patterns. This creates a natural context for considering their relevance in disciplines such as Pencak Silat.

Although interval training has been studied extensively in youth sports populations, its application to adolescent Pencak Silat athletes remains underexplored. The sport's unique combination of sustained striking phases, rapid stance transitions, and short rest intervals presents distinct physiological demands that justify tailored conditioning approaches. This study adapts a long-interval training protocol to address these demands and evaluates its effectiveness in improving aerobic efficiency and fat metabolism in a combat-sport–specific context.

Against this background, the study aimed to evaluate how a structured long-interval training program influences aerobic capacity, heart rate regulation, and body composition indicators in Pencak Silat athletes aged 16–18 years.

Materials and Methods

Participants

This study used a quasi-experimental pretest–posttest design with a comparison group and involved Pencak Silat athletes aged 16–18 years from East Java, Indonesia. Participants were recruited through convenience sampling from two sports-focused high schools. Twenty eligible athletes were randomly allocated to a long-interval training (LIT) group (n = 10) or a comparison group (n = 10) using sealed opaque envelopes. An independent researcher generated the random sequence and was not involved in recruitment or data collection. To maintain allocation concealment, the envelopes were sequentially numbered and opened only after completion of baseline assessments. This procedure was applied to reduce selection bias.

All athletes were required to be free from orthopedic injuries or metabolic disorders and to attend at least 90% of the training sessions. Athletes were excluded if they missed more than two sessions, joined additional structured conditioning programs, or sustained injuries that interfered with participation. The study was approved by the Ethics Committee of Universitas Negeri Surabaya. Informed consent was obtained from participants aged 18 years, and parental or guardian consent was obtained for those younger than 18.

Study Design

This study consisted of 16 supervised training sessions conducted three times per week. The long-interval training (LIT) protocol was applied only to the experimental group, while the control group continued their regular Pencak Silat training without structured interval work. Attendance was recorded at each session. Researchers also coordinated with the coach to ensure that training performed outside the study followed a lower intensity. Any reports of injury or discomfort were documented, and medical staff provided appropriate care.

VO_2max was assessed using the Multi-Fitness Test (MFT), a validated field protocol for adolescent athletes. Body fat percentage and visceral fat index were measured with the Xiaomi Smart Scale S400 (Xiaomi Inc., Beijing, China) using bioelectrical impedance analysis (BIA). All measurements were taken at baseline and after the final training session.

To ensure reliability, VO_2max and BIA assessments were conducted indoors at 22–24°C and 40–60% humidity and at the same time of day. Testing took place in the morning after an 8–10-hour fast. The MFT and the Xiaomi Smart Scale S400 were calibrated according to manufacturer instructions. Participants were asked to avoid strenuous physical activity, caffeine, and large meals for 12 hours before testing. For BIA, they emptied their bladder 30 minutes before measurement and maintained a consistent hydration level. All assessments were performed by the same trained examiner to ensure consistency.

Training program

The LIT intervention was structured over six weeks (16 sessions) and used running intervals prescribed according to each participant's Maximum Aerobic Speed (MAS). MAS was determined with the Multi-Fitness Test (MFT). The final level and duration reached before exhaustion were converted into MAS using the official MFT conversion table, which links the last completed level to the estimated maximal running speed associated with VO_2max. This MAS value was then used to individualize training intensity during the intervention.

Each session consisted of 180-second work intervals followed by 180-second active recovery at 40–50% MAS. Training was carried out in four small groups formed according to similar MAS values to ensure suitable pacing. The FITT structure of the program is presented in Table 1.

Across the intervention, intensity increased from 95% to 120% MAS, and training volume rose by adding repetitions and sets from week 3 onward. Recovery pace increased from 40% to 50% MAS in the later weeks. Total session duration ranged from approximately 24 to 36 minutes, excluding warm-up and cool-down. Heart rate was monitored with a Polar H10 device (Polar Electro Oy, Kempele, Finland) to control training intensity and confirm compliance. Heart rate was recorded continuously during each session to verify that participants remained within the planned intensity zones. Compliance was checked by reviewing the heart rate log after each session. Deviations from the target zones were documented and corrected during the following sessions.

All training sessions were conducted on an outdoor running track with a flat synthetic surface to maintain safety and consistency. Environmental conditions were monitored, and training was carried out only at temperatures of 26–30°C and in stable weather. Before each session, participants completed a 10–12-minute warm-up that included light jogging, dynamic stretching, and neuromuscular activation. The same warm-up routine and environmental conditions were used throughout the intervention.

The training structure was adapted to reflect the typical duration and intensity of Pencak Silat match segments, which involve intermittent exertion lasting 2–3 minutes with short active recovery. This alignment ensured that the LIT protocol remained relevant to real competition demands.

Statistical analysis

Normality was assessed using the Shapiro–

Table 1. Long-Interval Training Program Based on MAS

Week	Intensity (MAS %)	Work:Rest (s:s)	Repetitions (count)	Sets	Frequency (per week)	Goal of Adaptation
1	95	180:180	4	1	3	Aerobic tolerance development
2	100	180:180	4	1	3	Aerobic power activation
3	100	180:180	5	1	3	Increasing time at VO_2max
4	110	180:180	5	1	3	High-intensity stimulus
5	110	180:180	6	1	3	Aerobic power consolidation
6	120	180:180	6	2	3	Peak intensity and overload

Wilk test. Because several variables did not meet normality assumptions, within-group comparisons were performed using the Wilcoxon signed-rank test, and between-group differences were examined using the Mann–Whitney U test. Exact p-values and effect sizes are reported (two-tailed, $\alpha = 0.05$). Statistical analyses were carried out using IBM SPSS Statistics version 26 (IBM Corp., Armonk, NY, USA).

Results

The baseline characteristics of the participants showed that the two groups had comparable initial profiles (Table 2). There were no significant differences between the control and treatment groups in age ($p = 0.445$), resting heart rate ($p = 0.835$), systolic blood pressure ($p = 0.356$), diastolic blood pressure ($p = 0.673$), height ($p = 0.113$), weight ($p = 0.272$), BMI ($p = 0.849$), body fat ($p = 0.992$), visceral fat ($p = 0.425$), or baseline VO_2max values ($p = 0.111$). These results indicate that baseline characteristics were similar in both groups, with no statistically significant differences.

The pre–post changes in VO_2max, resting heart rate, body fat, and visceral fat in the control group are shown in Figure 1.

As shown in Figure 1, no significant pre–post differences were observed in the control group. VO_2max remained stable across both measurement points. Resting heart rate followed the same pattern. Body fat percentage and visceral fat levels also stayed within comparable ranges from baseline to post-intervention. Overall, Figure 1 indicates that the control group showed minimal change across all measured indicators.

Meanwhile, the pre–post changes in VO_2max, resting heart rate, body fat, and visceral fat in the treatment group are presented in Figure 2.

As shown in Figure 2, the treatment group demonstrated clear pre–post changes across all measured variables. VO_2max increased from baseline to post-intervention. Resting heart rate showed a lower post-intervention value compared with baseline. Body fat and visceral fat also decreased over the same period. Overall, Figure 2 shows a consistent shift in all indicators within the treatment group.

The between-group results for VO_2max, resting heart rate, body fat, and visceral fat are summarized in Table 3. As shown in the table, the treatment group demonstrated greater changes than the control group across all primary outcomes. VO_2max increased in the treatment group while remaining stable in the control group. Resting heart rate, body fat, and visceral fat decreased more in the treatment group than in the control group. These differences were reflected in statistically significant time × group effects for the main variables.

Across the intervention, the treatment group showed clear pre–post changes in VO_2max, resting heart rate, body fat, and visceral fat, while the control group remained largely unchanged. Between-group comparisons confirmed that these differences were greater in the treatment group, with statistically significant time × group effects across the main outcomes.

Discussion

This study aimed to evaluate how a structured long-interval training program influences aerobic capacity, heart rate regulation, and body composition indicators in Pencak Silat athletes aged 16–18 years. The results showed that long-interval training (LIT) increased VO_2max, lowered resting heart rate, and reduced both total and visceral fat compared with the control group. These changes indicate that LIT can produce cardiovascular and metabolic adaptations relevant to conditioning in youth combat sport athletes. The increase in VO_2max corresponds with studies reporting that interval-based methods lead to larger gains in aerobic fitness than moderate-intensity continuous exercise [16, 17]. HIIT and LIT formats may improve cardiorespiratory function through increases in stroke volume, cardiac output, and peripheral oxygen use [18, 19]. Intervals of 2–4 minutes, as applied in this study, have been associated with central adaptations such as

Table 2. Baseline characteristics of the study participants

Characteristics	Control (n = 10)	Treatment (n = 10)	p-value
Age (yrs)	16.90 ± 0.88	16.60 ± 0.84	0.445
RHR (bpm)	64.00 ± 3.23	64.30 ± 3.13	0.835
SBP (mmHg)	116.00 ± 5.16	118.00 ± 4.22	0.356
DBP (mmHg)	75.00 ± 5.27	76.00 ± 5.16	0.673
Height (m)	1.58 ± 0.08	1.63 ± 0.06	0.113
Weight (kg)	52.50 ± 8.89	56.20 ± 5.12	0.272
BMI (kg/m^2)	20.85 ± 2.09	20.99 ± 1.13	0.849
Body fat (kg)	17.22 ± 8.98	17.18 ± 9.09	0.992
Visceral fat (level)	2.60 ± 2.37	3.33 ± 1.53	0.425
VO_2max (mL/kg/min)	41.56 ± 4.78	44.48 ± 2.56	0.111

Note: Data are presented as mean ± SD. p-values were obtained using the independent-samples t-test.

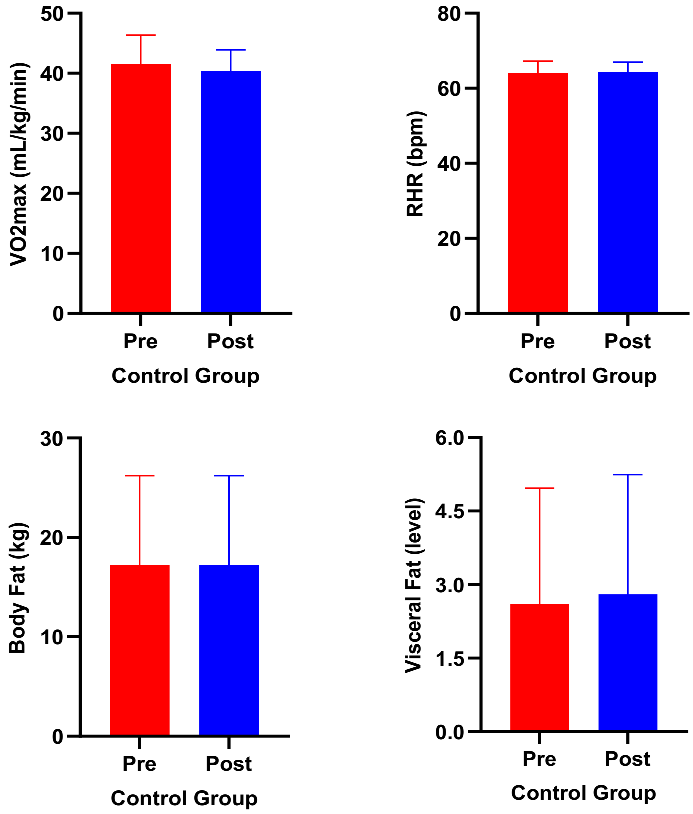

Figure 1. Pre–post changes in VO_2max, resting heart rate, body fat, and visceral fat in the control group
Note: Data are presented as mean ± SD. p-values were obtained using the paired-samples t-test.

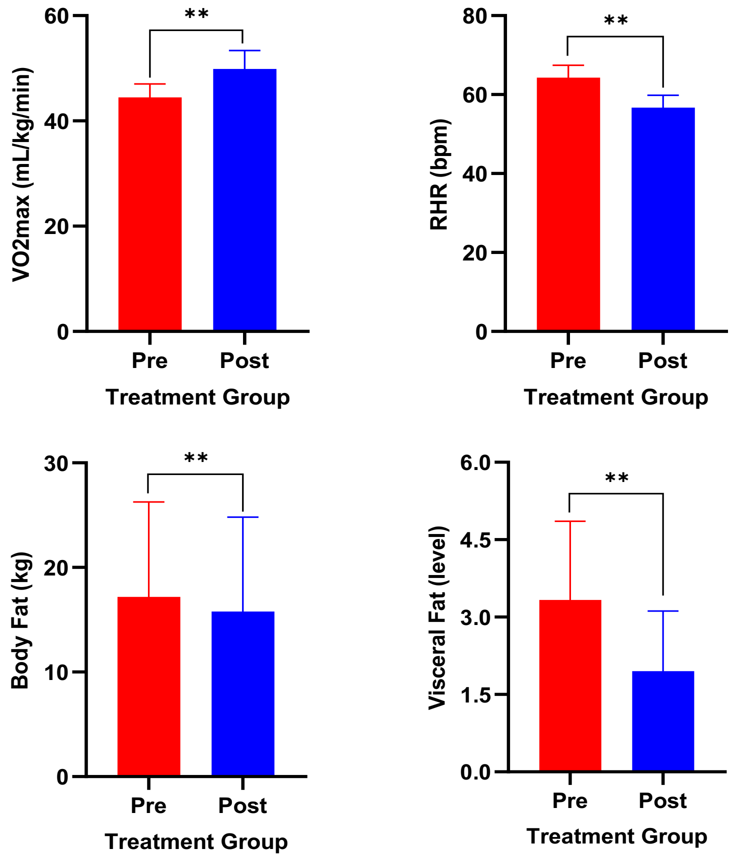

Figure 2. Pre–post changes in VO_2max, resting heart rate, body fat, and visceral fat in the treatment group
Note: Data are presented as mean ± SD. p-values were obtained using the paired-samples t-test. (**) Significant at pre ($p < 0.001$).

Table 3. Comparison of pre-, post-, delta, and percentage change values between treatment and control groups

Parameters	Control (n = 10)	Treatment (n = 10)	p-value	ES
Pre-VO_2max (mL/kg/min)	41.56 ± 4.78	44.48 ± 2.56	0.106	0.762
Pre-RHR (bpm)	64.00 ± 3.23	64.30 ± 3.13	0.835	0.094
Pre-Body Fat (kg)	17.22 ± 8.98	17.18 ± 9.09	0.992	0.004
Pre-Visceral Fat (level)	2.60 ± 2.37	3.33 ± 1.53	0.425	0.366
Post-VO_2max (mL/kg/min)	40.36 ± 3.56	49.85 ± 3.53**	0.001	2.679
Post-RHR (bpm)	64.30 ± 2.67	56.70 ± 3.13**	0.001	2.613
Post-Body Fat (kg)	17.24 ± 8.98	15.78 ± 9.04	0.721	0.162
Post-Visceral Fat (level)	2.80 ± 2.44	1.95 ± 1.17	0.339	0.444
Δ-VO_2max (mL/kg/min)	−1.20 ± 3.94	5.37 ± 2.75**	0.001	1.935
Δ-RHR (bpm)	0.30 ± 0.95	−7.60 ± 4.22**	0.001	2.582
Δ-Body Fat (kg)	0.02 ± 0.21	−1.40 ± 0.65**	0.001	2.962
Δ-Visceral Fat (level)	0.20 ± 0.42	−1.38 ± 0.71**	0.001	2.701
Change-VO_2max (%)	−2.31 ± 8.42	12.14 ± 6.27**	0.001	1.945
Change-RHR (%)	0.52 ± 1.54	−11.65 ± 6.44**	0.001	2.597
Change-Body Fat (%)	0.34 ± 1.73	−9.42 ± 4.73**	0.001	2.738
Change-Visceral Fat (%)	6.67 ± 14.05	−43.37 ± 18.13**	0.001	3.084

Note: Data are presented as mean ± SD. p-values were obtained using the independent-samples t-test. (**) Significant between groups ($p < 0.001$).

improved ventricular compliance and myocardial contractile function [20]. In adolescents, repeated efforts performed at 90–95% HRmax can stimulate mitochondrial development and enhance oxygen transport, contributing to higher aerobic efficiency [21]. For Pencak Silat athletes, these adaptations are relevant because the sport requires repeated high-intensity exchanges, rapid changes of direction, and intermittent striking sequences that rely on sustained aerobic capacity to maintain technical and tactical performance [22]. Evidence from other sports also indicates that long-interval formats can promote stronger cardiovascular and metabolic responses than short-interval protocols due to their longer work durations [4].

In addition to the increase in VO_2max, this study found a decrease in resting heart rate after six weeks of LIT. A lower resting heart rate reflects greater parasympathetic activity and higher stroke volume, which together indicate improved cardiac function [23, 24]. Comparable responses have been reported in adolescents participating in HIIT or circuit-based programs, where reductions of 5–10 beats per minute suggest increased vagal tone and better recovery capacity [25, 26]. Ingul et al. also showed that aerobic interval training improved left ventricular function and reduced heart rate both at rest and during submaximal workloads in obese adolescents, indicating improved autonomic regulation [20]. Other studies report that interval training can enhance heart rate variability (HRV), supporting more balanced autonomic control and better recovery in young athletes [24]. For Pencak Silat athletes, improved autonomic regulation may contribute to faster recovery between rounds and help maintain tactical focus during competitions. The combined increase in VO_2max and reduction in resting heart rate observed in this study reflects adaptations that improve oxygen delivery and reduce the number of cardiac contractions required during rest and exercise. These findings are consistent with the results reported by Eddolls et al. [18] and Ketelhut [23].

This study found reductions in both total and visceral fat following the LIT intervention. These outcomes are consistent with earlier research showing that high-intensity interval training can affect body composition and metabolic health [3, 27]. HIIT and LIT may stimulate fat oxidation through catecholamine-induced lipolysis, elevated post-exercise oxygen consumption (EPOC), and improvements in mitochondrial function [28]. Adolescents may respond well to these mechanisms because of higher metabolic flexibility and hormonal sensitivity during growth [26, 29]. The reduction in visceral fat observed in this study corresponds with reports that intermittent high-intensity exercise can lead to abdominal fat loss more effectively than continuous exercise [30, 31]. Wang et al. and Munhoz da Silveira Campos et al. also showed that interval and combined aerobic–resistance programs can improve abdominal fat distribution and metabolic indicators in youth populations [3, 32]. Meta-analytic findings indicate that HIIT can reduce total and visceral adiposity to a greater extent than moderate-intensity continuous exercise, particularly in programs lasting more than six weeks [14]. The present study showed that a six-week LIT program produced changes in visceral fat. Similar effects were reported by Francisco [21], who found that training performed near maximal aerobic velocity can influence visceral fat levels. From a sport-specific perspective, reductions in visceral fat may support improvements in agility, mobility, and movement speed in Pencak Silat, where rapid stance transitions and rotational actions are important. The combined changes in VO_2max, resting heart rate, and body composition observed in this study indicate that LIT can influence both cardiovascular function and metabolic regulation in adolescent athletes.

Heart rate responses recorded during the LIT sessions in this study were comparable to those reported in young gymnasts performing high-intensity circuits (83–89% HRmax). This similarity supports the use of HR monitoring as an indicator of internal training load [25]. The consistent HR patterns observed in this study indicate that the prescribed LIT intensity produced the required physiological stress for adaptation. Integrating HR and HRV monitoring into Pencak Silat training can provide coaches with tools to regulate training intensity, recovery, and workload [23]. This study also shows how HR- and HRV-based monitoring can be adapted for martial arts settings and aligned with the tactical and technical demands of Pencak Silat. The combination of reduced resting heart rate, increased VO_2max, and lower adiposity observed in this study reflects improvements in cardiac function, fat metabolism, and insulin sensitivity. These changes may support athletic performance and long-term health in adolescent athletes [29, 31].

While the physiological effects of interval training are well documented, this study provides applied insight into how long-interval training can be adapted for use in combat sport athletes during adolescence. Given the lack of existing data for this specific group, these findings offer practical implications for coaches designing conditioning programs in martial arts disciplines with similar physiological demands.

Despite these findings, several limitations should be considered. The six-week intervention period may have restricted the magnitude of long-term physiological changes. Earlier studies indicate that intervention durations of eight to twelve weeks can lead to wider changes in body composition and autonomic function [18, 21]. Dietary intake was not monitored, which may have affected the body fat results. The small sample size and the inclusion of only adolescent Pencak Silat athletes from a single competitive level also limit generalizability. Future studies should apply longer intervention periods, include female athletes and different age groups, and incorporate cardiac assessments such as HRV and echocardiography to obtain a clearer understanding of cardiovascular adaptations [20, 24].

From a practical perspective, this study indicates that LIT can be used as a sport-specific conditioning method for adolescent martial artists. Monitoring heart rate responses offers a simple and low-cost approach to managing training intensity and recovery. When combined with appropriate nutrition and progressive training load, long-interval training may help improve cardiovascular function, reduce abdominal fat, and support long-term athlete development in combat sports.

Conclusions

This study showed that long-interval training (LIT) increased aerobic capacity and reduced resting heart rate in Pencak Silat athletes aged 16–18 years. The lower resting heart rate suggests improvements in cardiac function and autonomic regulation. LIT also produced a reduction in visceral fat, indicating favorable changes in metabolic regulation and body composition. The change in total body fat was not statistically significant, which may reflect the relatively short intervention period or the absence of dietary monitoring.

The outcomes of the study correspond with the physiological demands of Pencak Silat, where repeated high-intensity actions require adequate aerobic capacity and efficient autonomic control. The combined changes in VO_2max, resting heart rate, and visceral fat support the use of LIT as a conditioning method for adolescent martial artists. The findings also illustrate how heart-rate–based indicators can be applied within a combat-sport context to monitor training responses and guide workload regulation.

LIT can therefore be considered a practical component of conditioning programs for adolescent athletes. Future research should extend the duration of interventions, include athletes of different ages and competitive levels, and incorporate cardiac assessments such as heart rate variability and echocardiography to build a clearer understanding of training-induced adaptations in combat sports.

Conflict of Interest

The authors declare no conflict of interest.

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