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Differential Neuromuscular Adaptations to Skill-Integrated versus Sprint-Based HIIT: Implications for Match-Specific Performance in Racket Sports

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Abstract

Background. Effective badminton performance requires sustaining a high level of physical effort while maintaining precise technical execution under fatigue. However, there is limited research comparing sprint-based high-intensity interval training (HIIT) and skill-integrated HIIT in terms of their physiological effects and transfer to match performance. HIIT is well established as an effective method for improving aerobic capacity and recovery.

Objectives. This study aimed to examine the effects of sprint-based HIIT and skill-integrated HIIT on aerobic capacity, autonomic recovery, metabolic clearance, smash accuracy, and smash speed in trained badminton players.

Materials and Methods. Thirty-six regional-level badminton players (aged 18–25 years) were stratified by age and baseline VO_2max and then randomly assigned to one of three groups: sprint-based HIIT (HSB; n = 12), skill-integrated HIIT (HSI; n = 12), or a control group (CON; n = 12). Both HIIT interventions followed an 8-week periodized program conducted three times per week, targeting 80–95% of maximal heart rate (HRmax). VO_2max was assessed using graded treadmill testing; heart rate recovery (HRR) was measured using Polar H10 monitors; and blood lactate concentration was determined using Accutrend Plus® analyzers at 5 and 10 minutes post-exercise. Smash accuracy was evaluated using a validated point-based target protocol, and smash speed was measured using radar. Data were analyzed using two-way repeated-measures ANOVA with Bonferroni post hoc corrections ($p < 0.05$). Effect sizes were calculated using Cohen's d.

Results. Both HSB and HSI groups demonstrated significant improvements in VO_2max (HSB: +6.7; HSI: +6.8 $ml \cdot kg^{-1} \cdot min^{-1}$, $p < 0.001$), HRR (HSB: +6.1; HSI: +6.5 bpm, $p < 0.001$), and metabolic clearance rate ($p < 0.01$), with effects exceeding those observed in the CON group ($p < 0.05$). Smash speed increased similarly in both HIIT groups (approximately +10 km/h, $p < 0.001$). However, HSI resulted in significantly greater improvements in smash accuracy compared to HSB (HSI: +8.1 vs. HSB: +4.7 points; $p = 0.002$), while the control group showed minimal changes across all variables.

Conclusions. Both sprint-based and skill-integrated HIIT effectively enhance physiological parameters in badminton players; however, only skill-integrated HIIT leads to substantial improvements in technical performance. Therefore, integrating high-intensity training with sport-specific skill execution appears to be optimal for competitive readiness.

Keywords: high-intensity interval training, badminton performance, neuromuscular adaptation, sport-specific conditioning, smash accuracy.

Introduction

Badminton is a high-intensity, intermittent sport characterized by rapid directional changes, forceful lower-body movements, repeated overhead strokes, and decision-making under fatigue (Ma et al., 2025; Rusdiana et al., 2023). These biomechanical and physiological requirements necessitate that athletes possess optimal aerobic capacity, rapid autonomic recovery, precise neuromuscular coordination, and the ability to maintain technical accuracy during high-intensity rallies (Rusdiana et al., 2020).

Traditional badminton training, generally defined by consistent conditioning, repetitive multi-shuttle drills, and non-periodized technical exercises, often fails to develop the integrated physiological and technical skills necessary for modern competitive performance (Alvarez-Dacal et al., 2025; Raibowo et al., 2024). This discrepancy highlights the urgent need for training frameworks that simultaneously enhance physiological readiness and performance capabilities within the constraints of match-specific conditions. The increasing emphasis on evidence-based conditioning in racket sports highlights the importance of interventions that can promote sport-specific adaptations while maintaining ecological validity.

Recent advancements in high-intensity interval training (HIIT) have offered a strategic alternative to conventional conditioning methods. Meta-analyses and empirical studies in racket sports, including tennis, squash, and badminton, indicate that HIIT leads to significant enhancements in VO_2max, heart rate recovery, metabolic efficiency, and anaerobic tolerance within brief training durations (Alibrahim & Hassan, 2024; Liu et al., 2024; Wiesinger et al., 2024). HIIT also helps the body reactivate autonomously and clear lactate more quickly, which are both important for keeping up rally performance and stroke quality (Kafrawi et al., 2025; Torma et al., 2019). Nonetheless, the majority of HIIT applications in badminton are non-specific, predominantly sprint-oriented and deficient in technical integration, consequently restricting the transference of physiological improvements to on-court performance (Bumrung et al., 2025). This limitation constitutes a significant deficiency in the existing literature.

To fill this gap, new research on skill-integrated HIIT suggests combining high-intensity workloads with technical and tactical elements that are specific to each sport. Research in tennis and squash demonstrates that the incorporation of stroke execution, footwork patterns, and decision-making into HIIT protocols markedly enhances racket velocity, accuracy, and movement efficiency more effectively than physical HIIT alone (Nugroho et al., 2024; Salem & Ismail, 2025; Zemková et al., 2024). In theory, this training specificity corresponds with ecological dynamics and motor learning principles, which assert that performance adaptation is optimized when training mirrors the perceptual–action couplings encountered in real match scenarios (Araújo et al., 2023). Despite this encouraging evidence, there is still a lack of controlled experimental studies evaluating the relative effects of sprint-based HIIT and skill-integrated HIIT on both physiological and performance outcomes pertinent to badminton matches.

This study's originality is in its direct comparison of sprint-based HIIT and skill-integrated HIIT through an 8-week periodized intervention and comprehensive outcome measures, including VO_2max, heart rate recovery, metabolic clearance rate, smash speed, and smash accuracy. This research rigorously analyzes both modalities within a quasi-experimental design employing well-trained regional-level athletes, unlike previous studies that examine one mode in isolation, hence ensuring high ecological validity. Moreover, technical performance metrics, especially smash accuracy have infrequently been assessed alongside physiological indicators within HIIT-based paradigms. This integrative assessment offers a novel comprehension of the role of neuromuscular coordination under fatigue in facilitating successful performance transfer.

Consequently, this study aimed to compare the effects of sprint-based and skill-integrated high-intensity interval training on physiological and match-relevant performance adaptations in trained badminton players. Based on principles of training specificity and ecological dynamics, it was hypothesized that both HIIT modalities would significantly improve aerobic capacity (VO_2max), heart rate recovery, and metabolic clearance compared to traditional training; however, skill-integrated HIIT would produce superior improvements in smash accuracy due to enhanced neuromuscular specificity and perceptual–action coupling under fatigue. Furthermore, it was expected that improvements in physiological recovery indices would be positively associated with changes in smash performance outcomes, reflecting a functional transfer of physiological adaptation to sport-specific technical execution.

Materials and Methods

The study's methodological framework is described in detail to guarantee openness and reproducibility. The ensuing subsections cover the participant characteristics, the intervention program's structure, the measurement protocols, and the statistical techniques used.

Study Participants

This quasi-experimental study involved thirty-six badminton players from East Java, aged 18 to 25, who participated at the regional level. Each player actively participates in competitive regional competitions and has at least five years of formal training experience. Invitations were disseminated via local badminton clubs to recruit participants, and interested individuals were assessed for eligibility.

Any prior musculoskeletal injuries within the last six months, a cardiovascular or metabolic disorder diagnosis, or current participation in a structured HIIT program were also criteria for exclusion. To guarantee the equilibrium of physiological profiles among the groups, individuals were segregated by age (18–21 versus 22–25 years) and baseline VO_2max quartiles before randomization. An independent research assistant executed stratified block randomization (block size = 6) via a computerized random number generator (Random.org).

Using the stratified block randomization technique, participants were randomly divided into three experimental groups. With no sport-specific technical components, the first group, the HIIT sprint-based group (HSB; n = 12), participated in high-intensity interval training that included general physical activities. The second group, the HIIT skill-integrated group (HSI; n = 12), engaged in training sessions tailored to badminton that combined technical and tactical elements such as multi-phase shot patterns, footwork drills, and smash execution with high-intensity intervals. The third group (CON; n = 12) was used as a control and carried on with their usual, traditional training regimens devoid of organized HIIT intervention. All participants gave written informed consent before data collection after being briefed on the study's methods, advantages, and possible risks. The

Universitas Negeri Semarang Research Ethics Committee examined and approved the study protocol (200/KEPK/FK/KLE/2025). Except for lactate analysis, which needed direct and instant post-exercise access, outcome assessors were blinded to group allocation during pre-test and post-test evaluations to reduce assessment bias.

Study Organization

The design of both the sprint-based and skill-integrated HIIT interventions was grounded in a periodization framework that aligns physiological overload with sport-specific neuromuscular demands. Rather than applying uniform high-intensity stimuli, the intervention structure was intentionally divided into progressive phases (foundation, intensification, power, and competition transfer) to ensure adaptive continuity and minimize neuromuscular redundancy. The sprint-based HIIT protocol was conceptualized to primarily target central and peripheral cardiovascular adaptations through repeated maximal locomotor actions, while the skill-integrated HIIT protocol was designed to elicit task-specific neuromuscular coordination under fatigue by embedding technical execution, perceptual–decision demands, and temporal pressure within the high-intensity framework.

This conceptual distinction was critical to the study's experimental logic, as it allowed for a direct comparison between non-specific physiological loading and ecologically valid, skill-oriented overload while maintaining comparable internal training intensity (80–95% HRmax). The intervention architecture therefore reflects a deliberate methodological choice to examine not only physiological adaptations but also the transferability of these adaptations to match-relevant technical performance.

A quasi-experimental pretest-posttest control group design was used for the 8-week intervention, which involved three weekly supervised sessions. Polar H10 heart rate monitors were used to carefully track training intensity, guaranteeing that target intensities (80–95% HRmax) were met. Attendance had to be higher than 80% to be included in the final analyses. The experimental groups adhered to programs that were periodized and divided into successive stages (Table 1).

The HIIT sprint-based protocol (Table 1) was meticulously periodized to maximize neuromuscular adaptations through progressive overload and phase-specific bioenergetic targeting. The four-phase structure—Foundation, Intensification, Power, and Tapering—systematically changed volume (reps/sets), intensity (80→95% HRmax), and rest periods to create different physiological stressors.

In contrast to the non-specific physiological demands of sprint-based HIIT, the skill-based intervention (Table 2) specifically targeted task-specific neuromuscular coordination under fatigue by integrating badminton's technical-tactical aspects into high-intensity frameworks.

Badminton-specific technical components were methodically incorporated into the high-intensity interval framework of the HIIT skill-based program. The development of basic movement patterns and technical proficiency was the main focus of the first half of the intervention (Weeks 1-4). To enhance agility, proprioception, and decision-making under fatigue, athletes engaged in cognitive-reaction exercises, shadow play with resistance bands, and six-point footwork circuits. Smash biomechanics training, which included kinematic chain drills and deception-based shot practices, came next. It aimed to improve upper-body power and stroke execution at 85–90% HRmax.

In the later phases (Weeks 5–8), the program progressed into match-representative scenarios. To replicate real-game intensity and tactical variation, drills featured rally-based shot sequences, high-pressure point play, and fatigue-induced decision-making. The final phase concentrated on competition transfer using full-sequence rally simulations, randomized shuttle anticipation tasks, and differential learning drills. These increasingly demanding sessions, which reached >95% HRmax, aimed to improve the neuromuscular coordination and physiological resilience needed for competitive badminton play.

Without being exposed to high-intensity interval structures, the control group trained in badminton according to a traditional regimen that mirrored preparation at the

Table 1. 8-week HIIT Sprint-based program

Weeks	Phase	Training Protocol	Intensity	Rest between sets	Rest between drills	Total Duration
1-2	Foundation	Dynamic warm-up (10 min) Shuttle run 20m: 5 sets x 10 repetitions Box jumps: 5 sets x 8 repetitions Burpees: 5 sets x 20 repetitions	80-85% HR max	60 sec	5 min	~80 min
3-4	Intensifikasi	Plyometric ladder drills: 10 sets (without interval rest) Sprint resisted 20m: 5 sets x 6 repetitions Medicine ball slams: 5 sets x 12 repetitions	85-90% HR max	60 sec	5 min	~90 min
5-6	Power	Depth jumps: 5 sets x 10 repetitions Sled pushes: 10 sets x 15m Tuck jumps: 5 sets x 20 repetitions	90-95% HR max	60 sec	5 min	~90 min
7-8	Tapering	Sport-specific agility drills: 5 sets Overspeed training: 5 sets x 20m Explosive starts: 5 sets x 10 repetitions	>95% HR max	60 sec	5 min	~80 min

Table 2. 8-week HIIT Skill-based program

Weeks	Phase	Training Protocol	Intensity	Rest between sets	Rest between drills	Total Duration
1-2	Footwork mastery	6-point footwork circuit: 5 sets x 60 s Shadow play with resistance bands (netting) Cognitive reaction drills (with tennis ball)	80-85% HR max	60 sec	5 min	~80 min
3-4	Smash biomechanics	Kinematic chain sequencing drills (Split-step to overhead smash) 25 min Deception skill practice (Cross-court drop shot disguised as smash) 25 min Smash power training: 10 sets x 15 repetitions	85-90% HR max	60 sec	5 min	~90 min
5-6	Match simulation	High-pressure point play (Targeted pressure drill): 5 sets x 4 min Fatigue-decision making drills (Smash-run-return drill) 5 sets x 20 repetitions Combination shot sequences (Smash-Net Partner Rally) 25 min	90-95% HR max	60 sec	5 min	~90 min
7-8	Competition transfer	Differential learning drills (Adaptive Smash Target Drill) 10 x 15 set Anticipation training (Random Shuttle Drill) 10 x 15 set Simulated tournament scenarios (clear → drop → netting → lift → smash) 25 min	>95% HR max	60 sec	5 min	~80 min

regional level. Under the guidance of the coach, training sessions were held three times a week and mostly comprised moderate-intensity technical drills, such as multishuttle drills, shuttlecock feeding, fundamental footwork patterns, and exercises involving stroke repetition. Physical conditioning was restricted to steady-state aerobic exercises like jogging and general dynamic stretching without any set intensity thresholds or performance evaluations. During the eight weeks, neither progressive overload nor periodization was used. To isolate the effects of HIIT, the control program purposefully did not include the structured work-rest ratios and sport-specific fatigue exposure found in the experimental groups. This method guaranteed ecological validity by simulating the standard procedure frequently employed by amateur badminton coaches in regional settings.

The Sport and Exercise Research Center (SERC) Laboratory and official indoor badminton courts approved by the Indonesian Badminton Federation served as the venues for all training and testing sessions. Participants were advised to avoid strenuous activity and caffeine for at least 24 hours before data collection and to keep regular sleep schedules during the study. Testing times were standardized for the morning (08:00–10:00 AM) to reduce circadian effects. All assessors adhered to a standard testing protocol, and calibration sessions before data collection helped establish interrater reliability among assessors. Participants were also asked to record their daily dietary intake and physical activity to track potential confounding factors.

Measurement

The selection of physiological outcome measures in this study was based on their sensitivity to high-intensity intermittent exercise and their relevance to recovery dynamics in badminton performance. Maximal oxygen uptake (VO_2max) was employed as an index of aerobic capacity underpinning repeated high-intensity rally participation, while heart rate recovery (HRR) was selected as a marker of autonomic reactivation and cardiovascular efficiency following maximal exertion. Blood lactate concentration and metabolic clearance rate (MCR) were included to capture post-exercise metabolic recovery, which is known to influence technical precision and movement stability under fatigue.

Importantly, these measures were not interpreted in isolation but as complementary indicators representing central (VO_2max), autonomic (HRR), and peripheral metabolic (MCR) adaptations. This integrative measurement rationale allowed for a multidimensional interpretation of training-induced adaptations and supported the examination of how physiological recovery capacity relates to technical performance outcomes such as smash accuracy and smash speed.

Every outcome measure was evaluated twice: once at baseline (pre-test) and once after the 8-week intervention (post-test). To reduce circadian variation, both tests were performed simultaneously (08:00–10:00 AM) in a standardized laboratory or on-court setting. For at least 24 hours before the test, participants were told not to engage in physically demanding activities or consume any caffeine or alcohol. A standardized dynamic warm-up preceded each measurement session, and all participants underwent the same testing procedures.

Heart rate recovery, maximal oxygen uptake (VO_2max), and blood lactate concentration were among the physiological parameters. The Accutrend Plus® portable analyzer (Roche

Diagnostics, Germany) was used to measure the amount of lactate in the blood. At the first and third minutes following the completion of an exercise regimen tailored to badminton and intended to elicit maximal effort, capillary blood samples were drawn from the fingertip. The findings were used as metabolic response indicators and reported in millimoles per liter (mmol/L).

Under laboratory conditions, a graded treadmill test (Bruce protocol) was used to determine maximal oxygen uptake (VO_2max). A calibrated breath-by-breath metabolic system (Cosmed Quark CPET, Italy) was used to measure oxygen consumption, and the highest 30-second rolling average was measured in $mL\cdot kg^{-1}\cdot min^{-1}$. After encouraging each athlete to reach volitional exhaustion, the test was stopped based on accepted clinical standards.

In the VO_2max treadmill test, heart rate recovery (HRR) was defined as the one-minute decrease in heart rate after maximal exertion. A Polar H10 heart rate sensor continuously measured heart rate, and readings were recorded in beats per minute (bpm). This measure served as a gauge for autonomic recovery ability (Bonato et al., 2018)and contrasted it with the smallest worthwhile change (SWC.

Smash accuracy and smash speed were among the performance outcomes. A badminton court fitted with rackets, shuttlecocks, a net, and a court marked with target zones for various scoring was used for the test. Participants received an explanation, examples, and two opportunities to try before the test. They then moved to their assigned positions, and after the tester delivered a long serve, they hit ten smashes into the opponent's court target area. The following rules apply to the assessment, which is based on where the shuttlecock lands: The shuttlecock scores 1 point if it lands on the single sideline 1.98 meters from the net with a width of 35 cm; 4 points if it lands 1.32 meters from the short service line; 5 points if it lands between 1.32 and 2.64 meters from the short service line; 3 points if it lands between 2.64 and 3.96 meters from the short service line; and 2 points if it lands directly on the long service line for singles. The highest score is awarded if the shuttlecock lands on the line between the two targets; if it lands outside the field or outside the target, the score is zero. After completing all smashes, the total scores from each attempt is used to determine the final score, indicating the participant's smash accuracy (Edmizal et al., 2022).

A Stalker ATS II radar gun (Stalker Radar, USA) was used to measure smash speed. It was positioned at shuttlecock height, two meters behind the player, to guarantee accurate velocity capture. Following a standardized warm-up, each player executed five maximal smashes; the fastest speed (km/h) was saved for analysis. Before data collection, test-retest reliability was established through pilot testing, and the same qualified staff gave all assessments to guarantee consistency.

Statistical Analysis.

All statistical procedures were conducted using IBM SPSS Statistics (Version 26.0; IBM Corp., Armonk, NY, USA). Data are presented as mean ± standard deviation (SD). Assumptions of normality and homogeneity of variance were evaluated using the Shapiro–Wilk and Levene's tests, respectively. For repeated-measures analyses, sphericity was assessed using Mauchly's test, with Greenhouse–Geisser corrections applied when necessary.

Training effects were examined using a two-way repeated-measures ANOVA with time (pre vs. post) as the within-subject factor and group (HSB, HSI, CON) as the between-subject factor. The primary parameter of interest was the time × group interaction, indicating differential training-induced adaptations. Significant interactions were followed by Bonferroni-adjusted post hoc comparisons. When distributional assumptions were violated, appropriate non-parametric alternatives were applied.

Effect sizes for ANOVA were expressed as partial eta squared ($\eta^2 p$), interpreted as small (0.01–0.05), medium (0.06–0.13), and large (≥0.14). Pairwise comparisons were quantified using Cohen's d. Associations between physiological and performance adaptations were explored using Pearson correlation coefficients. Statistical significance was set at $p < 0.05$.

An a priori power analysis was conducted using G*Power (Version 3.1.9.7) for a repeated-measures ANOVA (within–between interaction), assuming a large effect size ($f = 0.40$), $\alpha = 0.05$, and statistical power $(1 - \beta) = 0.80$. The minimum required total sample size was estimated at 30 participants.

To provide a more precise estimation aligned with the observed data, a post-hoc achieved power analysis was performed based on the interaction effect of the primary outcome (VO_2max). Based on the observed between-group differences and the significant time × group interaction ($p = 0.005$), the effect size was conservatively estimated at $f \approx 0.50$ ($\eta^2_p \approx 0.20$), corresponding to a large interaction effect. With $N = 36$, three groups, two measurement points, $\alpha = 0.05$, and an estimated correlation among repeated measures of 0.60, the achieved statistical power was calculated to be approximately 0.94.

Results

The following tables summarize the study's findings, starting with the performance and physiological adaptations observed in pre- and post-test assessments. The participant cohort was relatively homogeneous, consisting of 36 regional-level badminton players aged 18 to 25 (average age = 21.4 ± 2.1 years). Each player had at least five years of structured training experience. All groups' players displayed similar physiological and performance profiles at baseline: mean VO_2max values ranged from 47.1 ± 2.4 to 48.4 ± 3.2 $ml\cdot kg^{-1}\cdot min^{-1}$, resting heart rates were within the expected range for trained athletes, and initial smash performance was comparable (smash accuracy = 28.3 ± 4.4 to 28.8 ± 4.6 points; smash speed = 263.3 ± 5.0 to 269.6 ± 4.3 km/h). By clarifying the interpretability of later findings, these baseline similarities allow for greater confidence in attributing the observed adaptations to the intervention protocols rather than to pre-existing participant differences.

Sprint-based HIIT induced significant improvements in aerobic capacity, autonomic recovery, and metabolic clearance compared to baseline. Large effect sizes were observed for VO_2max and HRR, accompanied by meaningful improvements in smash speed and moderate gains in smash accuracy. Peak heart rate remained unchanged, indicating that performance gains were primarily driven by recovery and metabolic adaptations rather than maximal exertion capacity.

Skill-integrated HIIT produced comparable physiological improvements to sprint-based HIIT,

Table 3. Physiological and Performance Adaptations Following 8-Week Sprint-Based HIIT in Badminton Players

Variable		Mean±SD	Min	Max	Shapiro-Wilk test	Paired t-test	ES Cohen's d
VO_2 max (ml/kg/min)	Pre	47.14±2.39	42.16	49.94	0.241	0.000	2.192
	Post	53.89±3.64	49.8	61.48	0.159		
	Δpre-post	6.74±3.38	2.08	13.07	0.428		
Heart rate (bpm)	Peak HR_ Pre	195.17±3.41	191	202	0.671	0.574	0.242
	Peak HR_ Post	196.00±3.44	189	201	0.098		
	After 1 min_Pre	172.67±4.75	166	182	0.101	0.009	0.951
	After 1 min_Post	167.42±6.20	156	181	0.174		
	HRR_Pre	22.5±4.27	11	27	0.792	0.000	1.420
	HRR_Post	28.58±4.29	20	35	0.777		
	ΔHRR pre-post	6.08±2.87	1	11	0.542		
Blood Lactate (mmol/L)	5_min after exercise_Pre	12.29±1.45	10.15	14.32	0.837	0.010	1.029
	5_min after exercise_Post	11.07±0.84	9.07	11.89	0.426		
	10_min after exercise_Pre	11.63±1.07	10.18	13.85	0.402	0.000	2.826
	10_min after exercise_Post	9.03±0.74	7.86	10.16	0.531		
	MCR_Pre	0.66±1.09	-1.88	1.98	0.198	0.005	1.193
	MCR_Post	2.04±1.22	-0.97	3.82	0.768		
	ΔMCR pre-post	1.38±1.37	-0.81	4.91	0.280		
Smash Accuracy	Pre	28.67±3.47	23	36	0.081	0.000	1.312
	Post	33.33±3.63	27	39	0.685		
	Δpre-post	4.67±2.35	2	9	0.668		
Smash Speed (km/h)	Pre	263.29±4.99	256.43	273.32	0.305	0.000	1.883
	Post	273.19±5.51	261.14	280.81	0.777		
	Δpre-post	9.89±2.39	4.71	12.92	0.542		

HRR is heart rate recovery; MCR is Metabolic Clearance Rate; Δ is the difference between pre and post

Table 4. Physiological and Performance Adaptations Following 8-Week Skill-Integrated HIIT in Badminton Players

Variable		Mean±SD	Min	Max	Shapiro-Wilk test	Paired t-test	ES Cohen's d
VO_2 max (ml/kg/min)	Pre	48.36±3.16	44.54	55.96	0.129	0.000	2.264
	Post	55.13±2.81	50.94	59.66	0.193		
	Δpre-post	6.77±2.62	1.84	9.72	0.293		
Heart rate (bpm)	Peak HR_ Pre	197.75±7.28	180.00	208.00	0.064	0.564	0.188
	Peak HR_ Post	196.67±3.60	191.00	203.00	0.236		
	After 1 min_Pre	171.67±7.44	158.00	181.00	0.485	0.002	1.148
	After 1 min_Post	164.08±5.66	157.00	176.00	0.972		
	HRR_Pre	26.08±3.82	19.00	33.00	0.652	0.000	1.681
	HRR_Post	32.58±3.91	24.00	40.00	0.206		
	ΔHRR pre-post	6.5±2.58	0.00	10.00	0.740		
Blood Lactate mmol/L	5_min after exercise_Pre	12.79±0.99	10.64	14.27	0.493	0.091	0.529
	5_min after exercise_Post	12.32±0.77	11.10	13.63	0.255		
	10_min after exercise_Pre	11.46±0.71	9.90	12.70	0.309	0.000	2.384
	10_min after exercise_Post	9.58±0.86	8.13	10.91	0.645		
	MCR_Pre	1.33±0.48	0.54	2.03	0.493	0.003	1.489
	MCR_Post	2.74±1.25	0.96	5.50	0.890		
	ΔMCR pre-post	1.41±1.25	0.18	4.19	0.583		
Smash Accuracy	Pre	28.25±4.43	21.00	36.00	0.564	0.000	2.110
	Post	36.33±3.11	32.00	42.00	0.066		
	Δpre-post	8.08±2.54	3.00	12.00	0.581		
Smash Speed (km/h)	Pre	269.59±4.26	263.65	274.94	0.853	0.000	2.201
	Post	279.58±4.80	273.25	286.93	0.129		
	Δpre-post	9.99±2.86	4.01	13.63	0.193		

HRR is heart rate recovery; MCR is Metabolic Clearance Rate; Δ is the difference between pre and post

Table 5. Physiological and Performance Outcomes in the Control Group After 8 Weeks of Traditional Training

Variable		Mean±SD	Min	Max	Shapiro-Wilk test	Paired t-test	ES Cohen's d
VO_2 max (ml/kg/min)	Pre	48.23±3.27	43.62	54.06	0.747	0.109	0.656
	Post	50.51±3.67	45.29	55.69	0.245		
	Δpre-post	2.28±4.54	-4.69	12.07	0.809		
Heart rate (bpm)	Peak HR_ Pre	193.83±6.46	186.00	205.00	0.311	0.635	0.184
	Peak HR_ Post	195±6.28	185.00	205.00	0.664		
	After 1 min_Pre	166.33±9.54	151.00	182.00	0.571	0.512	0.189
	After 1 min_Post	164.58±9.02	152.00	180.00	0.813		
	HRR_Pre	27.5±6.65	12.00	40.00	0.087	0.005	0.433
	HRR_Post	30.42±6.85	17.00	43.00	0.335		
	ΔHRR pre-post	2.92±2.84	-3.00	7.00	0.567		
Blood Lactate mmol/L	5_min after exercise_Pre	12.85±0.99	11.26	14.27	0.071	0.097	0.319
	5_min after exercise_Post	12.54±0.95	11.32	13.72	0.793		
	10_min after exercise_Pre	11.50±0.93	10.12	12.52	0.552	0.078	0.530
	10_min after exercise_Post	11.02±0.88	9.73	12.67	0.521		
	MCR_Pre	1.35±0.46	0.68	1.98	0.071	0.391	0.281
	MCR_Post	1.52±0.72	0.12	2.60	0.603		
	ΔMCR pre-post	0.17±0.67	-0.87	1.58	0.273		
Smash Accuracy	Pre	28.83±4.59	21.00	35.00	0.062	0.000	0.661
	Post	31.75±4.24	24.00	39.00	0.268		
	Δpre-post	2.92±1.72	0.00	6.00	0.420		
Smash Speed (km/h)	Pre	265.03±4.49	259.90	275.26	0.751	0.000	1.143
	Post	270.41±4.91	264.85	279.27	0.747		
	Δpre-post	5.37±3.50	1.63	11.04	0.245		

HRR is heart rate recovery; MCR is Metabolic Clearance Rate; Δ is the difference between pre and post

Table 6. Between-Group Comparisons of Physiological and Performance Changes Across Sprint-Based HIIT, Skill-Integrated HIIT, and Control Conditions

Variable	Anova test	Group		p (sig.)	ES Cohen's d
ΔVO_2 max (ml/kg/min)	0.005	HSB	HSI	1.000	0.009
			CON	0.014*	1.114
		HSI	CON	0.013*	1.211
ΔHeart rate HRR (bpm)	0.006	HSB	HSI	1.000	0.154
			CON	0.025*	1.107
		HSI	CON	0.010*	1.319
ΔLactic acid MCR (mmol/L)	0.018	HSB	HSI	1.000	0.023
			CON	0.043*	1.122
		HSI	CON	0.036*	1.236
ΔSmash Accuracy	0.000	HSB	HSI	0.002*	1.394
			CON	0.191	0.849
		HSI	CON	0.000	2.379
ΔSmash Speed (km/h)	0.001	HSB	HSI	1.000	0.038
			CON	0.002*	1.508
		HSI	CON	0.002*	1.445

*Significant difference at p<0.05; Post hoc test using the Bonferroni test; ES refers to Effect Size.

particularly in VO_2max and HRR, but demonstrated a more pronounced enhancement in smash accuracy. The magnitude of technical improvement suggests a stronger transfer of training stimulus to match-relevant motor execution.

The control group exhibited only modest changes across physiological and performance variables, with substantially smaller effect sizes compared to both HIIT interventions, indicating limited adaptation under traditional training conditions.

Between-group comparisons confirmed that both HIIT modalities elicited superior physiological adaptations compared to the control condition. However, only skill-integrated HIIT demonstrated significantly greater improvements in smash accuracy relative to sprint-based HIIT, whereas no between-HIIT differences were observed for VO_2max, HRR, MCR, or smash speed.

Figure 1 visually illustrates the magnitude and trajectory of pre-to-post changes across all outcome variables. Both HIIT groups demonstrate steeper improvement slopes compared to the control condition for physiological markers and performance measures. Notably, the divergence between skill-integrated HIIT and sprint-based HIIT is most evident in smash accuracy, where the skill-integrated protocol shows a more pronounced upward shift. In contrast, physiological adaptations appear comparable between the two HIIT modalities, reinforcing the statistical findings presented in Table 6.

Discussion

The present study demonstrates that both sprint-based and skill-integrated HIIT significantly enhanced aerobic capacity, autonomic recovery, and metabolic clearance compared to traditional training. The magnitude of VO_2max

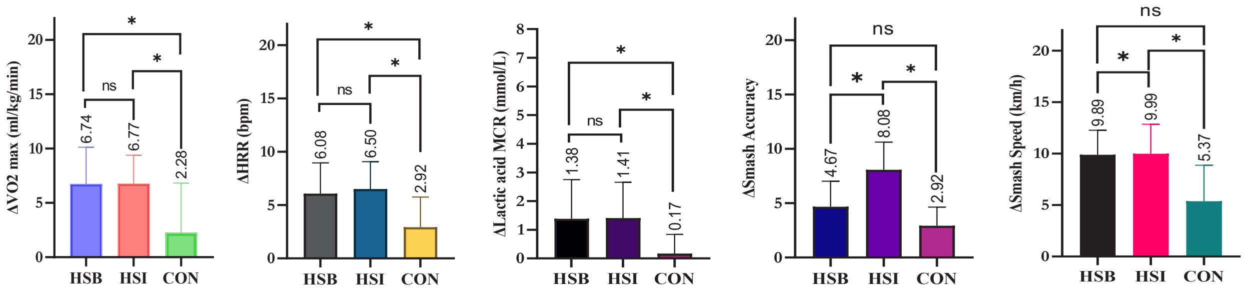

Fig 1. Graphical Representation of Pre-to-Post Intervention Changes in VO_2max, Heart Rate Recovery, Lactate Clearance, Smash Accuracy, and Smash Speed Among Groups. *significantly different; ns is not significantly different

improvement observed in both intervention groups is consistent with previous systematic reviews and meta-analyses reporting robust cardiorespiratory adaptations following HIIT in racket sport athletes (Alibrahim & Hassan, 2024; Liu et al., 2024; Wiesinger et al., 2024)while hemoglobin (Hb. Given the intermittent and high-intensity nature of badminton, improvements in aerobic capacity are particularly relevant for sustaining repeated high-intensity rallies and minimizing performance decrement across match duration (Cádiz Gallardo et al., 2023).

Both HIIT modalities also produced significant improvements in heart rate recovery (HRR), reflecting enhanced post-exercise autonomic reactivation. Faster HRR has been associated with improved cardiorespiratory fitness and competitive readiness (Plaza-Florido et al., 2019)HR has recently shown to be a stronger predictor of CRF than HRV in healthy young adults, yet these findings need to be replicated, in other age groups such as children. Therefore, this study aimed: (1, supporting the physiological relevance of the present findings. Similarly, the observed increases in metabolic clearance rate (MCR) indicate enhanced post-exercise lactate regulation, which is consistent with prior evidence suggesting that HIIT improves peripheral metabolic efficiency (Torma et al., 2019; Wiesinger et al., 2024). However, it is important to emphasize that molecular mechanisms such as monocarboxylate transporter upregulation were not directly assessed in this study; therefore, mechanistic explanations remain inferential rather than empirically confirmed.

Although physiological adaptations were comparable between HIIT formats, skill-integrated HIIT resulted in significantly greater improvements in smash accuracy compared to sprint-based HIIT. This finding aligns with the principle of training specificity, which posits that performance adaptations are optimized when training stimuli closely resemble competitive task demands (Araújo et al., 2023; Gabbett, 2006). Previous research in tennis and squash has shown that integrating technical execution within high-intensity training enhances stroke precision and performance transfer more effectively than non-specific conditioning alone (Irvan et al., 2024; Salem & Ismail, 2025). The present results extend this evidence to badminton, suggesting that embedding technical and decision-making components within high-intensity contexts may facilitate superior transfer to match-relevant motor execution.

Importantly, no significant differences were observed between the two HIIT modalities in VO_2max, HRR, MCR, or smash speed. This indicates that both training structures are similarly effective in eliciting central and peripheral physiological adaptations, likely through shared overload mechanisms characteristic of high-intensity interval stimuli (Astorino et al., 2017; Liu et al., 2024). The added benefit of skill-integrated HIIT appears to be performance-specific rather than physiological. However, this interpretation should remain within the limits of the measured variables. The present study did not include biomechanical motion analysis, electromyography, or perceptual-cognitive assessments; therefore, conclusions regarding neuromuscular coordination pathways or perceptual–action coupling mechanisms cannot be definitively established.

Taken together, these findings suggest that while structured HIIT effectively enhances physiological readiness in badminton athletes, the integration of sport-specific technical demands within high-intensity training may provide additional advantages for precision-dependent skills such as smash accuracy. Future investigations incorporating biomechanical and neurophysiological measurements are warranted to clarify the mechanisms underlying this performance transfer.

Conclusions

Both sprint-based and skill-integrated HIIT significantly enhanced aerobic capacity, autonomic recovery, metabolic clearance, and smash performance compared to traditional training. No meaningful differences were observed between HIIT modalities for physiological adaptations. However, skill-integrated HIIT resulted in superior improvements in smash accuracy, indicating a greater transfer to sport-specific technical performance.

These findings suggest that while high-intensity interval training is effective for improving physiological readiness in badminton players, integrating technical components within high-intensity contexts may provide additional performance-specific benefits. Future studies incorporating biomechanical and neuromuscular analyses are warranted to clarify the mechanisms underlying these adaptations.

Data and AI Transparency Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request. Due to ethical considerations and the protection of participant confidentiality, individual-level raw data are not publicly accessible. All aggregated data supporting the findings of this study are presented within the article.

The authors further declare that artificial intelligence (AI)-assisted tools were used solely for language editing and manuscript refinement. Specifically, QuillBot and Grammarly were utilized to improve grammatical accuracy, clarity, and academic writing style. No AI tools were used in study conception, methodological design, data collection, statistical analysis, data interpretation, or the generation of scientific conclusions. All scientific content and analytical decisions were independently developed and verified by the authors, who assume full responsibility for the integrity and accuracy of the manuscript.

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Conflict of Interest

All researchers declare that there is no conflict of interest in this research

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Диференційовані нейром'язові адаптації до високоінтенсивного інтервального тренування, інтегрованого з технічними діями, порівняно зі спринт-орієнтованим: наслідки для ігрової результативності у ракеткових видах спорту

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 11 с., 6 табл., 1 рис., 22 джерела.

Обгрунтування. Ефективна гра в бадмінтон вимагає підтримання високого рівня фізичного навантаження при одночасному збереженні точного технічного виконання в умовах втоми. Водночас існує обмежена кількість досліджень, що порівнюють спринт-орієнтований високоінтенсивний інтервальний тренінг (HIIT) та HIIT, інтегрований із технічними діями, з точки зору їх фізіологічного впливу та перенесення на ігрову діяльність. Відомо, що HIIT є ефективним засобом підвищення аеробної працездатності та відновлення.

Мета. Вивчити вплив спринт-орієнтованого HIIT та HIIT, інтегрованого з технічними діями, на аеробну працездатність, автономне відновлення, метаболічний кліренс, точність і швидкість смеша у тренованих гравців у бадмінтон.

Матеріали і методи. У дослідженні взяли участь 36 гравців у бадмінтон регіонального рівня (18–25 років), яких стратифіковано за віком і базовим рівнем VO_2max та випадково розподілено на три групи: спринт-орієнтований HIIT (HSB; n = 12), HIIT, інтегрований з технічними діями (HSI; n = 12), і контрольна група (CON; n = 12). Обидві HIIT-програми реалізовано протягом 8 тижнів за періодизованою схемою з частотою три рази на тиждень та інтенсивністю 80–95% від максимального серцевого ритму (HRmax). VO_2max оцінювали за допомогою градуйованого тесту на біговій доріжці; відновлення частоти серцевих скорочень (HRR) — з використанням моніторів Polar H10; концентрацію лактату в крові визначали за допомогою аналізаторів Accutrend Plus® через 5 і 10 хв після навантаження. Точність смеша оцінювали за валідованим протоколом із цільовою системою балів, швидкість смеша — за допомогою радару. Дані аналізували методом двофакторного дисперсійного аналізу з повторними вимірюваннями (ANOVA) із поправкою Бонферроні ($p < 0,05$). Розміри ефекту визначали за коефіцієнтом d Коена.

Результати. У групах HSB і HSI виявлено статистично значуще підвищення VO_2max (HSB: +6,7; HSI: +6,8 мл·кг$^{-1}$·хв$^{-1}$, $p < 0,001$), HRR (HSB: +6,1; HSI: +6,5 уд/хв, $p < 0,001$) та швидкості метаболічного кліренсу ($p < 0,01$), причому ці зміни перевищували показники контрольної групи ($p < 0,05$). Швидкість смеша зросла подібною мірою в обох HIIT-групах (приблизно +10 км/год, $p < 0,001$). Водночас у групі HSI зафіксовано значно більші покращення точності смеша порівняно з HSB (HSI: +8,1 проти HSB: +4,7 бала; p = 0,002), тоді як у контрольній групі зміни були мінімальними за всіма показниками.

Висновки. Спринт-орієнтований та інтегрований із технічними діями HIIT ефективно покращують фізіологічні показники гравців у бадмінтон. Водночас лише HIIT, інтегрований із технічними діями, забезпечує суттєве підвищення технічної результативності. Поєднання високоінтенсивного тренування зі специфічним виконанням технічних дій є оптимальним підходом до підготовки спортсменів до змагальної діяльності.

Ключові слова: високоінтенсивний інтервальний тренінг, результативність у бадмінтоні, нейром'язова адаптація, специфічна спортивна підготовка, точність смеша.

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