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Effects of an 8-week high-intensity interval training program on agility and intermittent endurance in junior badminton athletes

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Abstract

Background and Study Aim Sport-specific interval training is commonly incorporated into badminton conditioning programs to address the demands of repeated intensive actions performed during play. Training interventions focusing on the integration of sport-specific movement patterns under intermittent loading conditions are applied to influence performance-related outcomes during training and competition. Despite the use of different conditioning approaches, their relative effectiveness when integrated into regular training through sport-specific movement patterns remains a matter of practical interest. This study aimed to examine the effects of integrating an 8-week badminton-specific high-intensity interval training (BS-HIIT) program on agility and intermittent endurance in junior badminton athletes.

Material and Methods Forty competitive junior badminton athletes (13–17 years) were allocated to either a BS-HIIT group (n = 20) or a control group performing conventional conditioning (n = 20). Both groups trained twice weekly for eight weeks, in addition to regular technical training. The BS-HIIT protocol consisted of court-based, multidirectional movements replicating badminton footwork at 85–95% HR_max, whereas the control group performed general aerobic and agility-based conditioning. Agility was assessed using the Badminton Shuttle Run Agility Test (BSRAT), and intermittent endurance was evaluated using the Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1). A two-way repeated-measures ANOVA, effect size calculations, correlation analysis, and responder analysis were conducted.

Results Significant group × time interactions were observed for agility (η^2_p = 0.58) and intermittent endurance (η^2_p = 0.62). The BS-HIIT group demonstrated greater improvements in agility (−7.29%) and Yo-Yo IR1 performance (+31.4%) compared with the control group (−2.58% and +10.8%, respectively). A significant correlation between changes in intermittent endurance and agility was found only in the BS-HIIT group (r = −0.64, p = 0.002). A higher proportion of high responders was also observed following BS-HIIT.

Conclusions An 8-week badminton-specific HIIT program is more effective than conventional conditioning in improving agility and intermittent endurance in junior badminton athletes. Integrating sport-specific movement patterns within high-intensity conditioning appears to promote transferable and consistent performance adaptations.

Keywords: badminton-specific training, high-intensity interval training, agility performance, intermittent endurance, junior athletes

Introduction

Competitive badminton requires players to repeatedly execute explosive movements and rapid changes of direction while sustaining technical precision and tactical decision-making throughout prolonged match play. Elite and junior badminton players are required to sustain high movement intensity while maintaining technical precision and tactical decision-making under fatigue conditions [1]. Match analysis studies have demonstrated that competitive badminton involves frequent accelerations, decelerations, lunges, jumps, and multidirectional footwork, with rally durations ranging from 5 to 10 s interspersed by brief recovery intervals [2, 3]. Consequently, agility and intermittent endurance are widely recognized as important physical determinants of badminton performance, particularly in athletes transitioning to higher competitive levels [4].

In recent years, the increasing physical demands

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of modern badminton, driven by faster rally tempos, increased rally density, and greater tactical variability, have intensified the need for effective and time-efficient conditioning strategies [5]. Junior athletes, in particular, must develop sufficient physiological capacity to tolerate repeated high-intensity actions while simultaneously refining sport-specific movement skills [6]. However, traditional conditioning approaches in youth badminton programs often rely on general aerobic running, non-specific interval training, or isolated agility drills. These approaches may not adequately reflect the biomechanical and metabolic demands of actual match play [7, 8]. This mismatch between training stimuli and competition demands may limit the transfer of conditioning adaptations to on-court performance.

High-intensity interval training (HIIT) has emerged as an effective conditioning method for improving aerobic capacity, anaerobic performance, and intermittent endurance across a wide range of team and individual sports [9, 10]. HIIT protocols are known to elicit central and peripheral adaptations, including improvements in stroke volume, oxygen delivery, mitochondrial function, and metabolic efficiency, even when total training volume is relatively low [11, 12]. In intermittent sports, HIIT has been shown to outperform moderate-intensity continuous training in enhancing repeated-sprint ability and high-intensity running performance [13].

Despite the well-documented physiological benefits of HIIT, recent literature has emphasized that the effectiveness of training interventions is strongly influenced by the principle of specificity [14, 15]. Similar sport-specific HIIT approaches have been successfully implemented in other intermittent sports, such as on-court HIIT in tennis and squash or movement-integrated HIIT in handball. These approaches demonstrated improved transfer to sport-specific performance compared with generic running-based protocols [13, 16, 17]. Training stimuli that closely replicate sport-specific movement patterns, decision-making constraints, and work–rest structures are more likely to produce transferable performance gains [15]. In this context, sport-specific HIIT, in which high-intensity intervals are embedded within technical and movement patterns relevant to the sport, has gained increasing attention. Such approaches aim to integrate physiological conditioning with neuromuscular and coordinative demands, thereby promoting more holistic performance adaptations.

Within badminton research, however, the evidence base for badminton-specific HIIT remains limited. While several studies have examined the physiological profiles of badminton players or compared general HIIT with continuous training, relatively few controlled interventions have investigated HIIT protocols explicitly designed around badminton footwork, multidirectional movement, and rally-like intensities, particularly in junior athletes [18, 19]. Moreover, existing studies often focus on isolated outcomes, such as aerobic capacity or sprint performance. They do not simultaneously examine agility and intermittent endurance, two interrelated performance components in badminton. It is also important to note that most HIIT interventions previously applied in racket sports have predominantly employed generic running-based formats or non-specific interval drills. These formats primarily target cardiovascular adaptations with limited representation of sport-specific movement mechanics [10, 12]. In contrast, badminton performance involves frequent multidirectional accelerations, lunges, split-step actions, and rapid recovery movements performed under high metabolic stress [2, 3, 7]. These biomechanical and neuromuscular demands are insufficiently replicated by linear or generalized HIIT protocols. This may limit the transfer of training adaptations to on-court performance [14, 15]. Consequently, the effectiveness of HIIT programs that explicitly integrate badminton-specific footwork patterns and rally-like work–rest structures remains insufficiently explored, particularly in youth and junior athlete populations.

Another gap in the literature concerns the mechanistic relationship between improvements in intermittent endurance and agility performance following sport-specific conditioning. Agility in badminton is a multidimensional construct influenced by speed, strength, neuromuscular coordination, eccentric control, and fatigue resistance [20]. From a theoretical standpoint, enhanced intermittent endurance may delay fatigue-related declines in neuromuscular function. This may support faster and more efficient change-of-direction movements during repeated high-intensity actions [21]. However, empirical evidence linking endurance adaptations to agility improvements within a badminton-specific training context remains scarce, particularly in youth populations. Given these considerations, there is a need for controlled experimental research that evaluates the effectiveness of a badminton-specific HIIT (BS-HIIT) protocol on key performance determinants while addressing issues related to specificity, transferability, and individual responsiveness. Investigating such interventions in junior athletes is important, as this developmental stage represents a period for establishing physiological and neuromuscular foundations that underpin long-term athletic progression.

Furthermore, previous HIIT studies in racket sports and badminton have largely reported group-mean performance responses, with limited consideration of inter-individual variability in training adaptations [10, 18]. This represents a limitation, particularly in junior athletes, where differences in biological maturation, neuromuscular development, and training history may influence responsiveness to high-intensity training stimuli [15, 20]. Structured responder analysis has been increasingly advocated in applied sport science to enhance ecological validity and practical relevance. However, it remains rarely implemented in badminton-specific conditioning research [22, 23]. Addressing individual responsiveness may provide more nuanced insights into the consistency and effectiveness of sport-specific HIIT interventions in youth athlete development.

Several previous studies have investigated the effects of high-intensity interval training in racket sports and youth athlete populations, providing foundational evidence regarding the physiological benefits of HIIT [10, 12, 13, 18]. Systematic reviews and meta-analyses have demonstrated that HIIT is effective for improving aerobic capacity, repeated-sprint ability, and intermittent endurance across racket sports and combat-style activities [10, 12]. Similarly, intervention studies in youth athletes have reported positive adaptations following HIIT-based conditioning programs [13, 18]. However, these investigations have primarily employed generic running-based or non-specific interval formats and have focused predominantly on global physiological outcomes, with limited assessment of badminton-specific movement performance.

In badminton training practice, HIIT-based conditioning may be adapted to incorporate court-based, multidirectional footwork patterns representative of competitive match play. Such an approach allows high-intensity intervals to be embedded within movement structures that reflect the spatial and temporal demands of rallies. Performance assessment in this context commonly includes measures of agility and intermittent endurance, such as the Badminton Shuttle Run Agility Test (BSRAT) and the Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1), which reflect movement execution and repeated high-intensity effort capacity during rally-based play [3, 20, 24, 25, 26]. In junior athletes, these qualities are relevant in the context of ongoing neuromuscular and tactical development [22, 27]. Consideration of inter-individual variability in training responses represents an additional aspect of interest in youth conditioning research [28, 29].

Analysis of research findings has shown that high-intensity interval training is an effective conditioning approach for improving intermittent performance capacities in racket sports and youth athlete populations. Researchers emphasize the importance of aligning conditioning stimuli with the movement, temporal, and physiological demands of competitive play in order to support performance adaptations. At the same time, unresolved aspects related to the integration of sport-specific movement patterns, the interaction between key performance components, and individual variability in training responses continue to influence the practical application of HIIT in badminton training contexts. Addressing these considerations is essential for clarifying how conditioning strategies can be structured to support performance development in junior badminton athletes.

Based on the evidence discussed above, the evaluation of conditioning approaches that integrate sport-specific movement patterns within high-intensity interval training frameworks requires the identification of more effective training solutions. This study aimed to examine the effects of integrating an 8-week badminton-specific high-intensity interval training (BS-HIIT) program on agility and intermittent endurance in junior badminton athletes.

Materials and Methods

Participants

A total of 40 junior badminton athletes (male and female) aged 13–17 years participated in this study. Participants were recruited from established local badminton clubs in Surabaya City (Trisula Badminton Club and Training Ground Badminton Academy) through purposive sampling. This method is commonly applied in applied sport science research to ensure that participants possess relevant training backgrounds and performance characteristics [22, 27]. All athletes were actively engaged in systematic badminton training and competitive preparation at the regional level.

Eligibility criteria were defined to ensure sample homogeneity and to reduce confounding factors related to training status. Inclusion criteria consisted of the following:

- a minimum of four years of structured badminton training;
- a regular training frequency of at least four sessions per week;
- absence of musculoskeletal injury or illness for at least three months prior to the study.

Athletes with a history of cardiovascular, neurological, or metabolic disorders were excluded. Athletes participating in additional structured conditioning programs outside the study protocol were also excluded. These criteria are consistent with previous intervention studies investigating high-intensity training effects in youth and junior athletes [30].

Given the developmental characteristics of adolescent athletes, particular attention was paid to safety and training readiness. Prior to participation, all athletes underwent pre-participation screening. This screening included medical clearance from club-affiliated physicians and confirmation from coaches regarding training history and current health status. Written informed consent was obtained from parents or legal guardians, and assent was obtained from the athletes, in accordance with ethical guidelines for research involving minors [31]. The study was approved in accordance with the seven ethical principles of the World Health Organization (WHO) under approval number 129206/UN38.III.3/TU.00.00/2025.

Following baseline testing, participants were matched according to ranked pretest agility and intermittent endurance scores, assessed using the Yo-Yo Intermittent Recovery Test Level 1, to ensure equivalence between groups. Participants were ordered based on baseline performance, and pairs with the most similar scores were formed. Within each matched pair, participants were alternately assigned to either the experimental group (badminton-specific HIIT; n = 20) or the control group (conventional training; n = 20). This matched-pair allocation procedure was conducted manually by the research team and was not randomized. Matching procedures are recommended in applied sport settings where full randomization may be constrained by logistical or ethical considerations, while still maintaining acceptable internal validity in training intervention studies [28, 32].

Throughout the intervention period, training attendance and compliance were closely monitored. Athletes who missed more than 10% of the total training sessions were excluded from the final analysis. This threshold is commonly used in exercise intervention studies to ensure sufficient training exposure and data integrity [13].

Research Design

This study employed a controlled experimental design with a pretest–posttest parallel-group approach. The study was conducted over an 8-week intervention period, following the Consolidated Standards of Reporting Trials (CONSORT) principles adapted for sports science research. A structured and controlled training schedule was applied to compare the effects of a badminton-specific high-intensity interval training (BS-HIIT) protocol with those of conventional conditioning training. The overall organization of the study included baseline testing, intervention implementation, training load monitoring, and post-intervention testing. An overview of the study design and experimental protocol is presented in Figure 1.

At baseline (week 0), all participants underwent pre-intervention assessments of agility and intermittent endurance. Following baseline testing, participants were matched based on initial

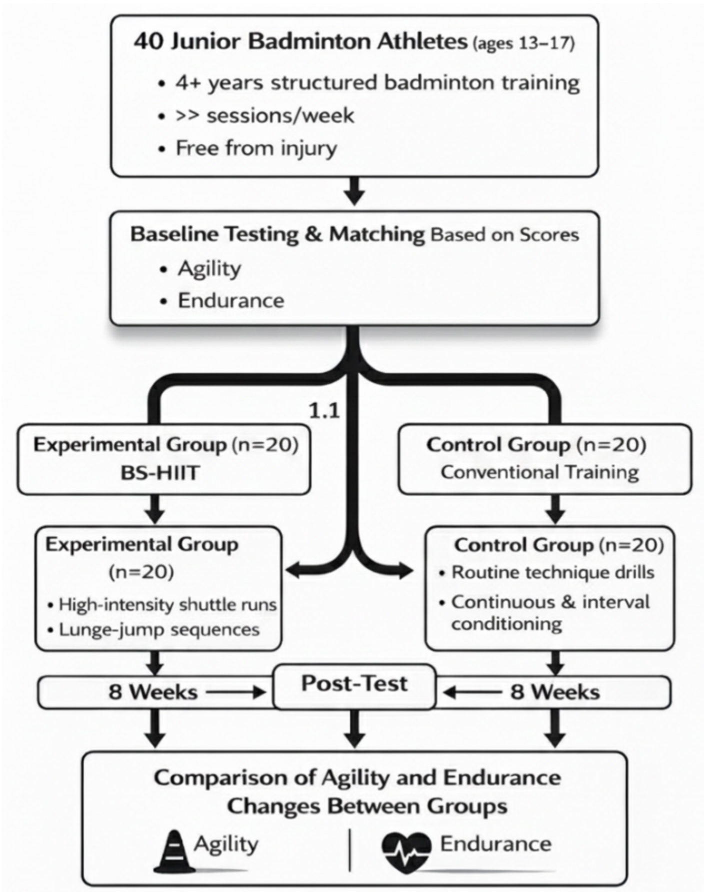

Figure 1. Study design and experimental protocol of the Badminton-Specific High-Intensity Interval Training (BS-HIIT) intervention.

performance scores and allocated into either the experimental group (BS-HIIT) or the control group (conventional training). Both groups continued their regular technical and tactical badminton training provided by their clubs. The conditioning component differed according to group assignment.

To control for training exposure, both groups completed two conditioning sessions per week, separated by at least 48 hours, in addition to routine badminton practice. Conditioning sessions were conducted on indoor badminton courts under the supervision of BWF-certified coaches and sport science researchers. Training attendance, session duration, and internal training load were monitored to ensure compliance and comparability between groups. A detailed description of the conditioning programs for both groups is provided in Table 1.

The conditioning training program constituted the primary intervention of this study. An overview of the conditioning characteristics for the experimental and control groups is presented in Table 1. The intervention was performed twice per week for eight weeks, while regular technical and tactical badminton training was maintained and not manipulated.

The intervention was periodized progressively across the 8-week program. Training intensity and complexity were increased every two weeks through manipulation of bout duration, movement complexity, and recovery time, following established principles of overload and progression in high-intensity training [27, 30]. A detailed description of the conditioning protocols applied across the intervention period is provided in Table 2.

Reactive change-of-direction (COD) tasks involved rapid changes in movement direction performed in response to randomized visual cues provided by the coach, indicating movement toward specific court zones. Game-like movement consisted of continuous multidirectional badminton footwork, including lunges, split steps, lateral shuffles, and recovery movements, performed across court areas without shuttle involvement. Smash–recovery multidirectional drills comprised simulated smash footwork followed by rapid recovery to the base position using forward, backward, and lateral movements. Intermittent rally simulation involved repeated high-intensity movement bouts structured to reproduce rally–rest patterns observed during badminton match play. The non-specific agility circuit included generic multidirectional drills without badminton-specific movement patterns, while the mixed aerobic–plyometric circuit combined cyclic aerobic exercises with basic plyometric tasks. Interval running was performed as repeated 2-min running bouts interspersed with 1-min passive recovery, whereas continuous running was conducted at a steady intensity of 65–75% HR_max for 15–25 min with progressive increases in duration.

Both groups completed two conditioning sessions per week over an 8-week intervention period (16 sessions in total). The experimental group followed a badminton-specific HIIT program, whereas the control group performed conventional conditioning with matched training frequency and session duration. Each conditioning session lasted approximately 25–30 min and consisted of a warm-up, a main conditioning phase, and a cool-down.

Measurement

Agility performance was assessed using a badminton-specific agility test designed to replicate multidirectional movement patterns commonly performed during competitive rallies [33]. The

Table 1. Conditioning training programs for experimental and control groups

Component	Experimental Group (BS-HIIT)	Control Group (Conventional Training)
Training frequency	2 sessions/week	2 sessions/week
Session duration	25–30 min	25–30 min
Warm-up (10 min)	Dynamic mobility, skipping, court footwork patterns	Jogging, dynamic stretching
Main training format	High-intensity interval training	Continuous and interval conditioning
Primary exercises	Multidirectional shuttle runs, lunge–jump sequences, lateral shuffles, smash-recovery footwork	Continuous running, agility ladder drills, basic plyometrics
Movement specificity	High (court-based)	Low–moderate (general conditioning)
Work–rest structure	30–40 s work / 20–30 s active recovery	Continuous or fixed intervals (1–3 min work)
Target intensity	85–95% HRmax, RPE 17–19	70–85% HRmax, RPE 13–16
Progression strategy	Increased repetitions, reduced recovery, added directional complexity every 2 weeks	Increased duration or repetitions
Cool-down (5 min)	Low-intensity movement, static stretching	Static stretching
Total intervention	8 weeks	8 weeks

Table 2. Detailed conditioning (intervention) programs for experimental and control groups (8 weeks, 16 sessions)

Week / Session (W–S)	Experimental Group – Badminton-Specific HIIT (BS-HIIT)	Control Group – Conventional Conditioning	Intensity Target
W1 – S1	Multidirectional shuttle (front–back–side), 3 × 30 s / 30 s	Continuous jogging + dynamic mobility, 15 min	85% HRmax, RPE 16
W1 – S2	Lateral shuffle + forward sprint, 3 × 30 s / 30 s	Agility ladder (basic patterns), 3 × 30 s	85% HRmax, RPE 16
W2 – S3	Lunge right–left + recovery step, 3 × 30 s / 30 s	Straight-line sprint drills, 6 × 20 m	85–88% HRmax
W2 – S4	Split-step → diagonal movement, 3 × 30 s / 30 s	Basic plyometric jumps (squat jumps), 3 × 10 reps	85–88% HRmax
W3 – S5	Court-based shuttle (6-point pattern), 4 × 30 s / 25 s	Interval running (1 min run / 1 min walk × 6)	88–90% HRmax
W3 – S6	Lunge + vertical jump, 3 × 35 s / 25 s	Agility cone drills (non-reactive), 4 × 30 s	88–90% HRmax
W4 – S7	Lateral shuffle + reactive COD, 4 × 30 s / 25 s	Continuous running, 18 min	88–90% HRmax
W4 – S8	Smash approach + recovery footwork, 3 × 35 s / 25 s	Basic plyometric circuit, 3 rounds	88–90% HRmax
W5 – S9	Random multidirectional shuttle, 4 × 35 s / 20 s	Interval running (90 s / 60 s × 6)	90–93% HRmax
W5 – S10	Lunge → jump → lateral recovery, 4 × 35 s / 20 s	Agility ladder (advanced patterns), 4 × 30 s	90–93% HRmax
W6 – S11	Continuous rally footwork simulation, 4 × 40 s / 20 s	Tempo running, 20 min	90–93% HRmax
W6 – S12	Diagonal sprint + backpedal, 4 × 35 s / 20 s	Cone shuttle run (linear), 4 × 40 s	90–93% HRmax
W7 – S13	Game-like random movement (cone/LED cue), 5 × 40 s / 20 s	Interval running (2 min / 1 min × 6)	93–95% HRmax
W7 – S14	Smash–recovery multidirectional, 4 × 40 s / 20 s	Agility circuit (non-specific), 4 rounds	93–95% HRmax
W8 – S15	Intermittent rally simulation, 5 × 40 s / 20 s	Continuous running, 22 min	93–95% HRmax
W8 – S16	COD under fatigue (lateral–forward patterns), 4 × 40 s / 20 s	Mixed aerobic–plyometric circuit	93–95% HRmax

test was conducted on an indoor badminton court with standardized markings corresponding to forward, lateral, diagonal, and backward movement directions. Participants started from the central base position and moved as quickly as possible to the designated targets following a fixed sequence. Performance was recorded as total completion time (s) using electronic timing gates (Brower Timing Systems, USA). Each participant completed two trials, separated by a 3-min passive recovery period, and the best performance was used for further analysis. This test has demonstrated good-to-excellent reliability (ICC = 0.87–0.94) and construct validity for assessing agility in racket sport athletes, including badminton players [16, 34]. A schematic representation of the test layout and movement sequence is shown in Figure 2.

The Badminton Shuttle Run Agility Test (BSRAT) is conducted on one half of a standard badminton court. The athlete stands approximately one meter behind the start/finish line while holding a badminton racket in the dominant hand. Upon the start signal or when the timing gate is triggered, the athlete sprints to the central square (point 1). From the center, the athlete moves to touch or knock over a shuttlecock placed at predetermined positions in eight different directions (points 2–8) following a fixed order. After each shuttlecock contact, the athlete returns to the central square and touches it with one foot before proceeding to the next direction. After completing the final shuttlecock contact, the athlete returns to the center and sprints back to the start/finish line to stop the timer. Each participant performs one familiarization trial followed by three to five valid trials, with sufficient passive recovery between attempts. Test performance is evaluated based on the total time required to complete the entire movement sequence, measured in seconds.

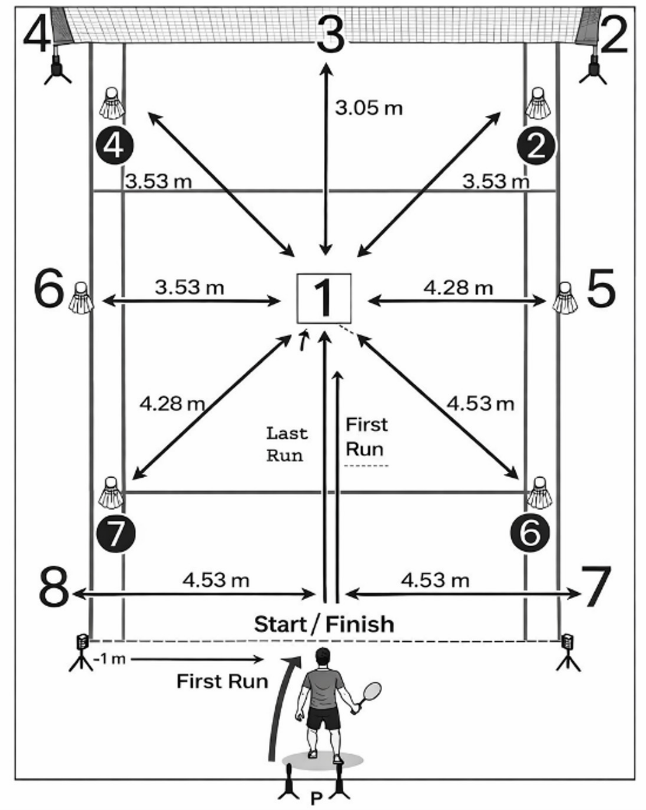

Figure 2. Badminton Shuttle Run Agility Test (BSRAT) [33]

The fastest valid trial is recorded as the final score. A time penalty of one second is added for each error, including failure to touch a shuttlecock or failure to touch the central square with the foot. Trials are repeated if the athlete performs the sequence in an incorrect order or does not complete the test. Shorter completion times indicate better agility and change-of-direction performance specific to badminton.

Intermittent endurance capacity was evaluated using the Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1) [24]. The test consists of repeated 20-m shuttle runs performed at progressively increasing speeds, interspersed with 10 s of active recovery, and continued until volitional exhaustion or failure to maintain the required pace on two consecutive occasions. Total distance covered (m) was recorded as the primary outcome variable. Heart rate was continuously monitored throughout the test using chest-strap heart rate monitors (Polar H10, Finland) to verify maximal effort. The Yo-Yo IR1 has demonstrated excellent test–retest reliability (ICC > 0.95) and is considered a valid measure of intermittent endurance in sports characterized by repeated high-intensity efforts, including badminton [25, 26].

Internal training load during each training session was quantified using the session rating of perceived exertion (sRPE) method [35]. Approximately 30 min after each session, athletes reported their perceived exertion using the Borg CR-10 scale [36]. Training load was calculated by multiplying session duration (min) by the reported RPE score and was expressed in arbitrary units (AU). The sRPE method has been shown to be a valid and reliable indicator of internal load in youth and adolescent athletes [37, 38].

Heart rate responses were recorded continuously during all training sessions using Polar H10 monitors [39]. Mean and peak heart rate values were extracted and expressed as a percentage of estimated maximal heart rate (%HR_max). Heart rate monitoring was used to verify training intensity and to ensure compliance with the prescribed high-intensity interval training protocol. This approach is widely recommended for physiological load monitoring in intermittent sports [17, 40].

All performance tests were conducted under standardized indoor conditions on a wooden badminton court, with ambient temperature maintained between 24–26°C. Prior familiarization sessions were conducted to minimize learning effects, and both the BSRAT and Yo-Yo IR1 have demonstrated acceptable test–retest reliability in adolescent and racket-sport populations (ICC > 0.85) [22, 24].

All measurements were conducted at baseline (pre-test) and after the intervention period (post-test) under standardized indoor conditions. Participants were instructed to refrain from vigorous physical activity for 48 h before testing and to maintain their usual dietary habits [41, 42] and hydration habits [43, 44]. All tests were administered by the same investigators using identical equipment and procedures to reduce measurement variability.

Agility performance was assessed using electronic timing gates (Brower Timing Systems, Draper, UT, USA) positioned at hip height (≈0.8 m) at the start/finish line. Athletes commenced each trial from a standardized standing start position with the lead foot placed 30 cm behind the gate to prevent premature triggering, and timing was initiated automatically upon breaking the infrared beam.

Heart rate (HR) responses during training sessions were continuously monitored using Polar H10 chest-strap monitors (Polar Electro Oy, Finland), which have demonstrated high validity for exercise HR measurement [45]. Maximal HR was estimated using an age-based equation (208 − 0.7 × age), and training intensity zones were defined relative to individual HR_max, with high-intensity efforts corresponding to 85–95% HR_max. Session compliance was verified through post-session HR data analysis. Both the BSRAT and Yo-Yo IR1 have demonstrated acceptable test–retest reliability in adolescent and racket-sport populations (ICC > 0.85) [24, 33].

Statistical Analysis

All data were analyzed using SPSS (version 27; IBM Corp., Armonk, NY, USA). Descriptive statistics are presented as mean ± standard deviation (SD). Normality of data distribution was assessed using the Shapiro–Wilk test, and homogeneity of variances was verified using Levene's test. Baseline comparability between groups was examined using independent-samples t-tests.

To evaluate the effects of the intervention on agility (Badminton Shuttle Run Agility Test, BSRAT) and intermittent endurance (Yo-Yo Intermittent Recovery Test Level 1), a two-way repeated-measures analysis of variance (ANOVA) was performed with time (pre-test vs. post-test) as the within-subject factor and group (BS-HIIT vs. control) as the between-subject factor. Partial eta squared (η^2_p) was calculated to quantify the magnitude of the group × time interaction effects. Within-group changes were further quantified using Cohen's d, calculated from pre–post mean differences divided by the pooled standard deviation. Relative performance changes were expressed as percentage change ((post − pre) / pre × 100), and between-group effect sizes for change scores were calculated to support practical interpretation of training effects.

Associations between changes in intermittent endurance and agility performance were examined using Pearson's product–moment correlation coefficients within each group, with statistical significance determined using two-tailed testing. To examine inter-individual variability in training responses, a responder analysis was conducted by classifying athletes as high or low responders based on a median split of individual pre–post change scores within each group for both performance outcomes. The number and percentage of athletes in each category were calculated. Statistical significance was set at $p < 0.05$ for all analyses.

Results

A total of 40 junior badminton athletes completed the 8-week intervention and were included in the final analysis, with no dropouts due to injury or insufficient training compliance. Baseline characteristics were comparable between the badminton-specific HIIT (BS-HIIT) group and the control group, with no meaningful differences observed in age, sex distribution, anthropometric variables, training experience, or pre-intervention performance outcomes (Table 3).

Table 3. Baseline characteristics of the study participants (mean ± SD)

Variable	BS-HIIT (n = 20)	Control (n = 20)	p-value
Age (years)	15.15 ± 1.42	15.30 ± 1.34	0.73
Sex (male/female)	11 / 9	10 / 10	—
Height (cm)	161.20 ± 7.82	163.46 ± 7.78	0.36
Body mass (kg)	56.78 ± 8.68	57.00 ± 7.74	0.92
Training experience (years)	6.2 ± 1.24	6.0 ± 1.38	0.61
Agility (BSRAT, s)	17.16 ± 0.76	17.05 ± 0.91	0.66
Yo-Yo IR1 distance (m)	1139 ± 135	1123 ± 109	0.68

Note. Values are presented as mean ± SD. No significant between-group differences were observed at baseline ($p > 0.05$).

Table 3 shows that the BS-HIIT and control groups were comparable at baseline, with no significant differences in age, sex distribution, anthropometric variables, training experience, agility performance (BSRAT), or intermittent endurance (Yo-Yo IR1) ($p > 0.05$). Following confirmation of comparable baseline characteristics between groups (Table 3), the effects of the training intervention on agility and intermittent endurance performance were examined (Table 4).

Changes in agility and intermittent endurance performance over time are illustrated in Figure 3, while corresponding numerical values and effect size estimates are reported in Table 4. A two-way repeated-measures ANOVA revealed significant group × time interactions for both outcomes. The BS-HIIT group demonstrated a larger reduction in BSRAT completion time (Δ = −1.25 s, d = −1.61) compared with the control group (Δ = −0.44 s, d = −0.47), with a large proportion of explained variance (η^2_p = 0.58). Similarly, Yo-Yo IR1 performance increased substantially following BS-HIIT (Δ = +357 m, d = 2.48), exceeding the improvement observed

Table 4. Effects of BS-HIIT on agility and intermittent endurance performance

Outcome	Group	Pre-test	Post-test	Δ Change	Cohen's d	η^2_p (Time × Group)
Agility (BSRAT, s)	BS-HIIT (n=20)	17.16 ± 0.76	15.91 ± 0.79	−1.25	−1.61	0.58
	Control (n=20)	17.05 ± 0.91	16.61 ± 0.93	−0.44	−0.47	
Yo-Yo IR1 (m)	BS-HIIT (n=20)	1138.6 ± 134.9	1495.7 ± 152.6	+357.1	2.48	0.62
	Control (n=20)	1122.8 ± 109.1	1244.5 ± 115.9	+121.7	1.08	

Note. Values are presented as mean ± SD. Δ Change represents the post–pre difference. Cohen's d reflects within-group standardized change. Partial eta squared (η^2_p) represents the magnitude of the group × time interaction derived from two-way repeated-measures ANOVA.

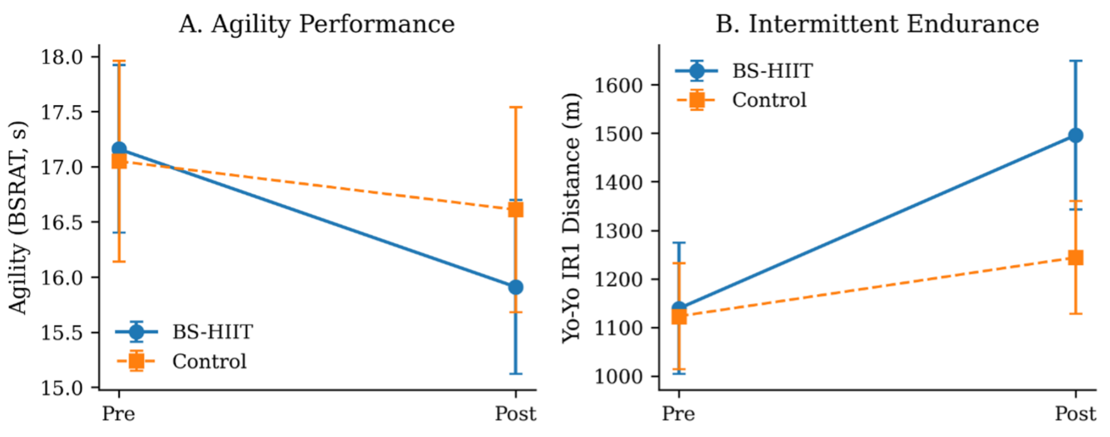

Figure 3. Change over time in performance outcomes

in the control group (Δ = +122 m, d = 1.08). The group × time interaction for intermittent endurance accounted for 62% of the explained variance (η^2_p = 0.62). To complement these findings, relative changes and between-group effect sizes were subsequently examined.

Relative percentage changes in performance outcomes and between-group effect sizes were examined to provide additional insight into the magnitude of training-induced adaptations following the intervention. An overview of relative (%) changes and between-group standardized differences for agility and intermittent endurance is presented in Table 5.

The results indicate that BS-HIIT elicited greater relative improvements in both agility and intermittent endurance compared with conventional training (Table 5). To further examine the relationship between adaptations in these performance outcomes, associations between changes in intermittent endurance and agility performance were analyzed (Table 6).

The relationships between individual changes in intermittent endurance and agility performance within each group are summarized in Table 6.

The relationship between changes in intermittent endurance and agility performance following the intervention is illustrated in Figure 4.

As shown in Figure 4, a significant negative correlation was observed in the BS-HIIT group ($r = -0.64$, $p = 0.002$), indicating that greater improvements in intermittent endurance were associated with larger reductions in agility completion time. No significant association was found in the control group.

Correlation analysis demonstrated a significant association between changes in intermittent endurance and agility performance within the BS-HIIT group, whereas no such relationship was observed in the control group. Given the observed inter-individual variability in training responses, athletes were subsequently classified according to their responsiveness to the intervention. The results of the responder analysis for agility and intermittent endurance improvements are presented in Table 7.

Responder analysis indicated a higher proportion of high responders in the BS-HIIT group compared with the control group for both agility and intermittent endurance outcomes (Table 7). Specifically, a greater percentage of athletes in the BS-HIIT group demonstrated meaningful improvements in BSRAT performance and Yo-Yo IR1 distance, whereas the control group showed a higher proportion of low responders across both performance measures.

Table 5. Relative (%) changes and between-group effect sizes following BS-HIIT

Outcome	Group	Pre-test	Post-test	% Change	Cohen's d (between-group)
Agility (BSRAT, s)	BS-HIIT	17.16 ± 0.76	15.91 ± 0.79	−7.29%	1.24
	Control	17.05 ± 0.91	16.61 ± 0.93	−2.58%	
Yo-Yo IR1 (m)	BS-HIIT	1138.6 ± 134.9	1495.7 ± 152.6	+31.4%	1.38
	Control	1122.8 ± 109.1	1244.5 ± 115.9	+10.8%	

Note. Percentage change was calculated as (post−pre)/pre × 100. Cohen's d represents the between-group standardized difference in change scores.

Table 6. Correlations between changes in intermittent endurance and agility performance

Variable Pair	r	p-value	Interpretation
Δ Yo-Yo IR1 vs. Δ BSRAT (BS-HIIT)	−0.64	0.002	Large
Δ Yo-Yo IR1 vs. Δ BSRAT (Control)	−0.31	0.18	Small–moderate

Note. Δ values represent post-test minus pre-test values. Negative correlation coefficients indicate that greater improvements in intermittent endurance were associated with larger reductions in agility completion time.

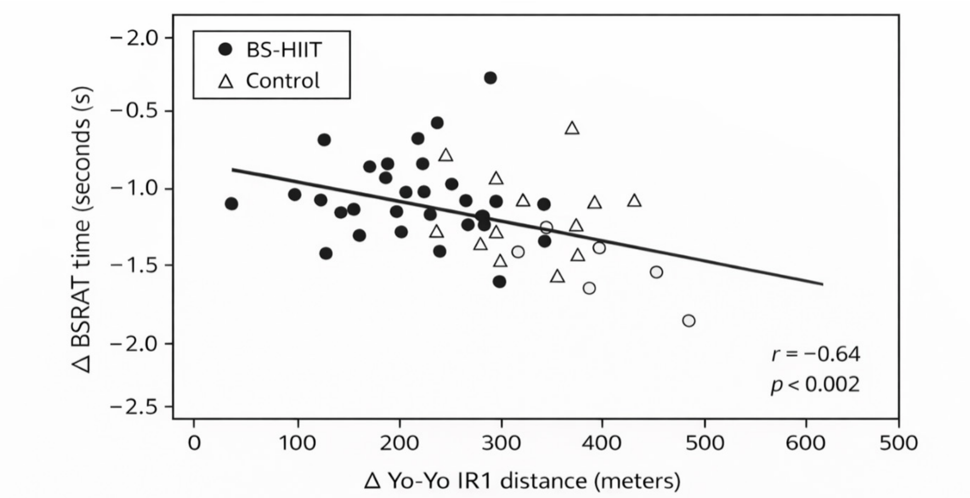

Figure 4. Relationship between changes in intermittent endurance (Δ Yo-Yo IR1) and agility performance (Δ BSRAT) following the intervention.

Table 7. Responder analysis for agility and intermittent endurance improvements

Outcome	Group	High Responders n (%)	Low Responders n (%)
Agility (BSRAT)	BS-HIIT	14 (70%)	6 (30%)
	Control	7 (35%)	13 (65%)
Yo-Yo IR1	BS-HIIT	15 (75%)	5 (25%)
	Control	8 (40%)	12 (60%)

Discussion

The present study investigated the short-term effects of a badminton-specific high-intensity interval training (BS-HIIT) program on physiological load, intermittent endurance, and agility performance in competitive badminton athletes. The main findings indicate that BS-HIIT induced greater improvements in Yo-Yo IR1 performance and agility (BSRAT) compared with conventional training, along with a higher internal load as reflected by heart rate distribution and energy expenditure. In addition, a significant association was identified between changes in intermittent endurance and agility performance, indicating interrelated adaptations between physiological capacity and sport-specific movement efficiency.

The BS-HIIT protocol elicited a higher internal load, as evidenced by greater time spent in high-intensity heart rate zones and increased total energy expenditure compared with the control condition. These findings suggest that BS-HIIT effectively replicated the intermittent, high-intensity physiological demands characteristic of competitive badminton rallies, which typically involve repeated accelerations, decelerations, and short recovery periods [2, 3].

Sustained exposure to heart rates above 85–90% HR_max is known to stimulate central and peripheral cardiovascular adaptations, including increased stroke volume, improved oxygen delivery, and enhanced mitochondrial efficiency [46, 47]. The higher cumulative cardiovascular strain observed in the BS-HIIT group likely contributed to the greater gains in intermittent endurance capacity observed in the Yo-Yo IR1 test. These responses were achieved without extending total training duration, indicating the time efficiency of sport-specific HIIT as a conditioning strategy.

The improvement in Yo-Yo IR1 performance following BS-HIIT reflects an enhanced ability to tolerate repeated high-intensity efforts interspersed with brief recovery periods. In badminton, intermittent endurance is an important determinant of match performance, as players are required to sustain explosive movements and rapid changes of direction over prolonged match durations [8, 48]. These findings are consistent with previous research showing that high-intensity interval training produces greater improvements in intermittent endurance than moderate-intensity or non-specific conditioning programs [12, 13]. The badminton-specific design of the BS-HIIT drills likely enhanced training transfer by engaging sport-relevant muscle groups, movement patterns, and neuromuscular coordination under metabolic stress, supporting the principle of training specificity [15].

Agility performance, assessed using the BSRAT, improved to a greater extent in the BS-HIIT group than in the control group. This result suggests that repeated exposure to high-intensity, multidirectional movement tasks under fatigue enhanced the ability to execute rapid directional changes efficiently. Agility in badminton depends not only on speed but also on neuromuscular coordination, eccentric strength, and reactive control [49, 50].

The BS-HIIT protocol likely promoted neuromuscular adaptations by repeatedly challenging braking and re-acceleration capacities under time pressure and metabolic stress. These adaptations may include improved motor unit recruitment, enhanced intermuscular coordination, and greater movement economy during high-intensity actions [43, 44]. Such mechanisms help explain why agility gains were more pronounced in the BS-HIIT group despite similar technical training exposure between groups. A key finding was the significant correlation between changes in Yo-Yo IR1 performance and changes in BSRAT performance within the BS-HIIT group. Athletes who demonstrated greater improvements in intermittent endurance also exhibited larger enhancements in agility performance. This relationship was not observed in the control group, suggesting that the integration of endurance and movement-specific demands within the BS-HIIT protocol contributed to linking these adaptations.

This finding provides empirical support for a mechanistic linkage between physiological capacity and sport-specific performance. Improved intermittent endurance may delay fatigue-related neuromuscular impairments, allowing athletes to maintain rapid footwork, precise positioning, and efficient change-of-direction mechanics during repeated high-intensity efforts [23, 51]. Consequently, endurance adaptations should be viewed as foundational elements that support the execution of complex motor tasks in intermittent sports such as badminton.

From a theoretical perspective, the present results reinforce integrative models of performance adaptation that emphasize interactions between physiological, neuromuscular, and task-specific constraints. Rather than treating conditioning and skill development as separate entities, the BS-HIIT approach demonstrates that conditioning stimuli embedded within sport-specific contexts can simultaneously enhance physiological capacity and movement performance [52, 53]. The observed inter-individual variability in adaptation further supports contemporary frameworks advocating individualized training prescription and monitoring. Athletes may respond differently to identical training stimuli depending on baseline fitness, neuromuscular characteristics, and recovery capacity [29, 54]. Thus, integrating internal load monitoring with performance testing remains essential for optimizing training outcomes.

From an applied standpoint, the findings suggest that incorporating badminton-specific HIIT sessions into regular training programs can effectively improve both intermittent endurance and agility without increasing total training volume. Coaches may consider prioritizing drills that combine high-intensity movement, rapid directional changes, and short recovery intervals to maximize transfer to competitive performance. Monitoring heart rate responses and energy expenditure may assist practitioners in ensuring that training intensity remains within targeted physiological zones.

Beyond group-level effects, the responder analysis provides insight into the heterogeneity of training adaptations following the BS-HIIT intervention. The identification of high and low responders indicates that junior badminton athletes do not adapt uniformly to standardized high-intensity training stimuli. Such variability may be influenced by differences in biological maturation, neuromuscular coordination, and prior training exposure, which are known to modulate responsiveness to high-intensity exercise during adolescence [22, 27, 28]. From a practical perspective, distinguishing responder profiles enables coaches to move beyond uniform conditioning prescriptions and adopt more individualized training strategies.

Low responders may require adjustments in training volume, recovery duration, or movement complexity to optimize adaptation, whereas high responders may benefit from progressive overload to further enhance sport-specific movement efficiency and intermittent endurance [28, 29]. This individualized approach aligns with contemporary long-term athlete development frameworks, which emphasize personalized progression and injury risk reduction during sensitive developmental periods in youth sports [22, 33]. Therefore, the responder-based findings extend beyond descriptive classification and offer a practical framework for optimizing badminton-specific conditioning in junior athletes.

Limitations of the study

Several limitations should be acknowledged. The study focused on short-term adaptations and did not assess long-term retention or transfer to competitive match outcomes. In addition, direct measures of neuromuscular or metabolic mechanisms were not included. Future research should integrate biomechanical analyses, muscle activation measures, and match-play performance indicators to further elucidate the pathways linking endurance and agility adaptations. Longitudinal studies examining different competitive levels and age groups would enhance the generalizability of the findings.

Conclusions

The findings of this controlled trial indicate that an 8-week badminton-specific high-intensity interval training (BS-HIIT) program is associated with greater improvements in agility and intermittent endurance compared with conventional conditioning in junior badminton athletes. The larger gains observed in badminton-specific agility performance and Yo-Yo IR1 outcomes suggest an enhanced ability to sustain repeated high-intensity actions while maintaining efficient sport-specific movement patterns. Moreover, the significant relationship between changes in intermittent endurance and agility highlights the integrative nature of physiological and neuromuscular adaptations induced by sport-specific HIIT. From an applied perspective, BS-HIIT represents a practical and time-efficient conditioning approach that can be incorporated into regular training schedules to improve key physical capacities relevant to competitive badminton without increasing overall training volume.

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Conflict of Interest

The authors report no conflict of interest.

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