

# Blood Flow Restriction with Low-Intensity Functional Training Improves Lower-Limb Strength Balance in Amateur Badminton Players: A Randomized Controlled Training Intervention

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## Article

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# Abstract

Asymmetric movement patterns in badminton may contribute to lower-limb strength imbalance, injury risk, and limited sport-specific performance. This randomized controlled training intervention examined whether 8 weeks of blood flow restriction combined with low-intensity functional training improves lower-limb strength, strength balance, and badminton-related performance in amateur badminton players. Forty-eight healthy amateur badminton players with a China Badminton rating of Level 3 or above were allocated to blood flow restriction combined with low-intensity functional training (BFR+LIFT), high-intensity functional training (HIFT), or low-intensity functional training (LIFT); 46 completed the intervention. Relative peak torque at the hip, knee, and ankle, strength-balance indices, and badminton-related performance were assessed before and after training. BFR+LIFT and HIFT produced broad improvements in lower-limb isokinetic strength and were generally superior to LIFT. BFR+LIFT showed selected advantages for knee flexor bilateral asymmetry, knee flexion-to-extension ratio, and 30-m sprint performance, whereas between-group differences in agility and badminton-specific movement tasks were less consistent. These findings suggest that BFR+LIFT may be an effective low-load strategy for improving lower-limb strength and selected strength-balance and sprint-related outcomes in amateur badminton players.

Trial registration: Chinese Clinical Trial Registry (ChiCTR), ChiCTR2600127180. Registered 26 June 2026. Retrospectively registered.

## Introduction

Badminton is a racket sport characterized by repeated lunges, rapid accelerations and decelerations, multidirectional changes of direction, and a single-handed playing pattern. These sport-specific demands may contribute to asymmetrical lower-limb loading and strength development. Previous studies have shown that badminton players may exhibit bilateral asymmetry in concentric strength of the hip, knee, and ankle joints, as well as imbalances between agonist and antagonist muscle groups in the lower limbs [1]. Because efficient badminton movement depends on coordinated force transmission through the hip, knee, and ankle joints, lower-limb muscle strength imbalance may adversely affect movement control, sport-specific performance, and lower-limb injury risk [2].

According to the Standards for Skill Level Evaluation in Badminton issued by the Chinese Badminton Association, amateur badminton players rated Level 3 or above generally have relatively systematic technical skills, long-term participation experience, and a certain level of physical fitness. Unlike beginners, whose primary goal is often general health promotion, these players usually aim to further improve sport-specific fitness and competitive performance, in order to achieve better results in amateur competitions and reduce the risk of lower-limb injuries associated with repeated training and competition. Therefore, improving lower-limb muscle strength imbalance in this population is important for optimizing movement patterns, enhancing badminton-related performance, and lowering injury risk. However, because amateur players may vary in strength-training experience, movement control, and recovery capacity, high external resistance loads may not always be suitable for them. Moreover, systematic intervention studies targeting lower-limb strength balance in this specific population remain limited. Thus, identifying a practical training strategy that can improve lower-limb strength and strength balance while controlling mechanical load is of practical importance for amateur badminton players.

Muscle strength balance refers to the ability of the body, under neuromuscular regulation and in response to internal and external stimuli, to achieve coordinated contraction of agonist and antagonist muscles at an appropriate length-tension relationship and torque ratio, thereby maintaining both static postural stability and efficient movement patterns during dynamic tasks. Its internal basis includes anatomical characteristics, biomechanical features, and physiological function, whereas its external manifestation is efficient motor control. From a structural perspective, muscle strength balance can be divided into intralimb balance, which refers to the torque ratio between agonist and antagonist muscles within the same joint, and interlimb balance, which refers to the symmetry between the left and right limbs or between the dominant and nondominant sides. Muscle strength imbalance can disrupt motor programs and sensorimotor integration, leading to compensatory movements, altered movement patterns, and an increased risk of injury. Therefore, interventions aimed at correcting muscle strength imbalance should adopt an integrated task-specific approach, among which functional strength training has been considered an effective strategy [2].

Functional strength training can improve muscle strength balance through multi-joint, closed-chain, and task-specific resistance and control exercises, thereby optimizing the torque ratio and length-tension coordination between agonist and antagonist muscles and enhancing bilateral symmetry of lower-limb strength [3]. Core-control and lumbopelvic-stability exercises are an important component of functional training because they may improve force transmission through the trunk-pelvis-lower-limb kinetic chain and reduce compensatory movement patterns during unilateral and multidirectional tasks. In addition, functional training, characterized by multi-joint closed-chain movements and enhanced proprioceptive demands, can improve movement control and the quality of technical

execution under unstable conditions. It also emphasizes eccentric braking and optimization of energy transfer, thereby reducing unnecessary energy expenditure and improving braking-reacceleration efficiency [4]. Thus, this training modality is well suited to the technical demands of rapid movement and precise stroke execution in badminton, as well as to the mechanical demands associated with sudden stopping, starting, and repeated changes of direction. However, although functional strength training can enhance neural drive and kinetic-chain coordination in nonbalanced, closed-chain, and multi-joint tasks, its effects on muscle cross-sectional area and metabolic stimulation remain relatively limited because of restricted external loading and its predominant reliance on neural adaptation. Consequently, there is still room for improvement in maximal strength and muscular symmetry.

Blood flow restriction training (BFRT), also known as KAATSU training or vascular occlusion training, is a training method in which specialized pressurizing equipment is used to restrict blood flow velocity, thereby creating a specific physiological loading stimulus during exercise [5]. Compared with traditional high-load strength training, low-intensity resistance training performed under blood flow restriction at 40% 1RM has been reported to produce effects highly comparable to those of traditional high-intensity resistance training performed at 65%-85% 1RM [6]. Previous studies have shown that BFRT can induce neuromuscular adaptations and recruit a greater number of motor units during exercise. Because of its unique physiological loading stimulus, BFRT creates a hypoxic and ischemic intramuscular environment that promotes recruitment of more type II muscle fibers, enhances their activation, and ultimately increases muscle cross-sectional area and muscle strength [7]. In addition, the accumulation of metabolic by-products in muscle stimulates the secretion of growth hormone (GH) and insulin-like growth factor-1 (IGF-1), which may facilitate training adaptations and, through circulation, may also enhance muscles in nonrestricted regions [8]. These physiological mechanisms provide theoretical support for combining BFRT with functional training to improve training effectiveness.

Furthermore, the mechanical stress imposed by high-load training requires participants to have adequate neuromuscular control and movement technique. Amateur players may find it difficult to maintain proper movement execution over time, which may increase the risk of joint and tendon injuries. By contrast, BFRT offers a safer alternative with comparable efficacy, lowers the entry threshold for training, and provides a feasible balance between safety and training effectiveness. The combination of BFRT and functional training may therefore offer complementary advantages. Specifically, BFRT may serve as an additional internal load and create a dual-load stimulus composed of internal and external loading, reducing external resistance while increasing physiological stress, further promoting the expression of muscle synthesis-related growth factors and enhancing the effects of functional strength training.

Therefore, this study recruited amateur badminton players with a China Badminton rating of Level 3 or above and implemented an 8-week randomized controlled training intervention. Based on the aforementioned literature and theoretical analysis, we hypothesized that blood flow restriction training combined with low-intensity functional training (BFR+LIFT) would be superior to low-intensity functional training alone (LIFT) in improving lower-limb muscle strength, muscle strength balance, and badminton-related performance. In addition, we expected that BFR+LIFT would produce strength gains comparable to those of high-intensity functional training (HIFT), while showing greater advantages in muscle strength balance and badminton-related performance. Specifically, we proposed the following hypotheses: (a) relative peak torque of hip, knee, and ankle flexion and extension at  $60^{\circ}\cdot s^{-1}$  would significantly increase, with greater improvements than in the LIFT group and effects comparable to those of the HIFT group; (b) muscle strength balance indices, including agonist/antagonist ratios and bilateral differences, would show greater optimization; and (c) badminton-related performance, as assessed by the T-test, badminton court lateral change-of-direction test, badminton court multi-directional "Mi"-shaped movement test, and 30-m sprint, would show more comprehensive improvement. After the 8-week intervention, this study systematically evaluated the effects of BFR+LIFT, HIFT, and LIFT on the above indicators, with the aim of providing a scientific and efficient training strategy for amateur badminton players that integrates performance enhancement with injury prevention, and of offering a theoretical basis for individualized physical training in populations who are not suitable for high external loads.

## Methods

### Experimental approach to the problem

This study used a randomized, assessor-blinded, three-arm, parallel-group controlled training-intervention design. The intervention was conducted at Beijing Normal University from May to July 2025. A total of 48 participants were allocated in a 1:1:1 ratio to one of three groups: blood flow restriction combined with low-intensity functional training (BFR+LIFT), high-intensity functional training (HIFT), or low-intensity functional training (LIFT), with 16 participants in each group. The BFR+LIFT group performed low-intensity functional training with blood flow restriction, the HIFT group performed high-intensity functional training, and the LIFT group performed low-intensity functional training. All three groups trained three times per week for 8 weeks. Isokinetic muscle strength tests at  $60^{\circ}\cdot s^{-1}$  and

badminton-related performance tests were conducted before and after the intervention to compare changes in relative peak torque, muscle strength balance, and performance among the three groups.

This study was designed as a sports science training intervention in healthy amateur badminton players, rather than as a clinical or therapeutic trial. The intervention consisted of structured exercise-training protocols and did not involve patients, disease diagnosis, medical treatment, drug administration, surgery, or patient-centered clinical outcomes.

## Participants

The required sample size was calculated using G\*Power 3.1 software, following the approach used in a previous BFR-related training study [9]. Based on previous research [10], the effect size was set at 0.55, the statistical power at 0.80, and the significance level at 0.05, yielding a minimum required sample size of 36 participants. To account for potential attrition and to ensure the validity of the experimental data, 48 participants were recruited, with 16 participants planned for each group.

Participants were recruited through poster advertisements from Beijing Normal University and Beijing University of Posts and Telecommunications in April 2025. The intervention was conducted from May to July 2025. A convenience sample of amateur badminton players who met the eligibility criteria and volunteered to participate was enrolled. Participants received a small gift after completing the study.

The inclusion criteria were as follows: (a) 18–30 years of age; (b) a China Badminton rating of Level 3 or above; (c) participation in badminton at least once per week; (d) no current lower-limb injury affecting training or testing; (e) no previous experience with blood flow restriction training; and (f) voluntary participation in the study. A Level 3 or higher rating indicates that participants were not beginners and had stable badminton participation with basic technical and competitive experience. Participants were excluded if they had any pulmonary or cardiovascular disease; uncontrolled hypertension; a history of thrombosis, varicose veins, or other conditions affecting venous return; coagulation disorders or current use of anticoagulant medication; neurological disorders; recent lower-limb surgery; current musculoskeletal injury that could affect training or testing; or previous experience with BFR training. Eligibility was screened using a health-history interview and baseline measurements of resting blood pressure, resting heart rate, thigh circumference, and leg circumference. These measurements were obtained on the first day of baseline testing.

After eligibility screening and written informed consent, baseline assessments were completed before group allocation. Participants were then randomly allocated to the BFR+LIFT, HIFT, or LIFT group using a random-number sequence generated in SPSS 27.0. Outcome assessors who conducted the baseline and post-intervention assessments were not informed of group allocation. Because of the visible nature of the BFR intervention and the different training intensities, participants and trainers could not be blinded. The data analyst was not blinded to group allocation.

During the intervention, two participants withdrew during the first week because of scheduling conflicts unrelated to the intervention, including one participant in the BFR+LIFT group and one participant in the HIFT group. Therefore, 46 participants completed the post-intervention assessments and were included in the complete-case analysis, including 15 in the BFR+LIFT group, 15 in the HIFT group, and 16 in the LIFT group. Participants who completed the study attended all 24 supervised training sessions, and missed sessions were completed through make-up sessions. No training-related adverse events were reported by participants or observed by the research staff during the intervention. The participant flow, including enrollment, randomization, attrition, and final analysis, is shown in Fig. 1. There were no significant differences among the groups in baseline characteristics, including age, sex, height, body mass, China Badminton rating, and weekly badminton frequency ( $P > 0.05$ ), indicating comparability at baseline (Table 2). In addition, no significant between-group differences were observed in baseline characteristics or pre-intervention outcome measures, indicating that the groups were comparable before the intervention. All participants were informed of the study procedures and provided written informed consent before participation. This investigation was conducted according to the Declaration of Helsinki, and the study protocol was approved by the Ethics Committee of the College of P.E. and Sports, Beijing Normal University (Approval No. TY20250406; April 6, 2025). The study was retrospectively registered in the Chinese Clinical Trial Registry (ChiCTR; registration number: ChiCTR2600127180) on 26 June 2026. The study was designed to evaluate exercise-training adaptations in healthy participants rather than clinical treatment effects.

## Procedures

All three groups underwent an 8-week training intervention, with training sessions performed three times per week. Each session lasted approximately 80 min. Before each session, all participants completed a standardized preparatory warm-up. The exercise selection was identical across groups and included core-control and lumbopelvic-stability exercises, unilateral lower-limb strength exercises, dynamic balance tasks, and ankle plantarflexor strengthening. Specifically, the program included weighted dead bug exercises, loaded farmer's walks over 15 m, weighted bird-dog exercises, single-leg Romanian deadlifts, Bulgarian split squats, weighted BOSU lunge jumps, BOSU lateral split squats holding a weight plate, and single-leg weighted calf raises. The weighted dead bug, loaded farmer's walk, and weighted bird-dog exercises were included as core-control components of the functional training program to target trunk control, lumbopelvic stability, and force transmission between the trunk and lower limbs. For unilateral exercises, 15 repetitions were completed on each side.

Training intensity was operationalized as relative external load. The BFR+LIFT and LIFT groups trained at 30% of exercise-specific estimated 1RM, whereas the HIFT group trained at 70% of exercise-specific estimated 1RM. For loaded farmer's walks, intensity was prescribed relative to the maximum 15-m carry load, defined as the maximum load that could be carried for 15 m with correct posture and without stopping. This low-intensity prescription falls within the 20%-40% 1RM range commonly recommended for low-load BFR resistance exercise, whereas the 70% prescription is consistent with conventional moderate-to-high resistance-training loads [11, 12]. A 60-s inter-set rest interval was used across all groups to control training density. Loads were individualized and adjusted when necessary to ensure that participants completed the prescribed repetitions with correct technique and without loss of balance. All training sessions were supervised by research staff or coaches to ensure correct technique, adherence to the prescribed protocol, and training safety. Participants were instructed not to perform additional lower-limb resistance training or BFR training during the intervention period. The training protocol is summarized in Table 1.

Table 1  
Training Protocol for the Three Intervention Groups

| Exercise                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Sets × reps / distance | BFR+LIFT intensity          | HIFT intensity              | LIFT intensity              | Inter-set rest |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|-----------------------------|-----------------------------|-----------------------------|----------------|
| Weighted dead bug exercise                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 3 × 15 reps            | 30% estimated 1RM           | 70% estimated 1RM           | 30% estimated 1RM           | 60 s           |
| Loaded farmer's walk                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 3 × 15 m               | 30% maximum 15-m carry load | 70% maximum 15-m carry load | 30% maximum 15-m carry load | 60 s           |
| Weighted bird-dog exercise                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 3 × 15 reps each side  | 30% estimated 1RM           | 70% estimated 1RM           | 30% estimated 1RM           | 60 s           |
| Single-leg Romanian deadlift                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | 3 × 15 reps each side  | 30% estimated 1RM           | 70% estimated 1RM           | 30% estimated 1RM           | 60 s           |
| Bulgarian split squat                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 3 × 15 reps each side  | 30% estimated 1RM           | 70% estimated 1RM           | 30% estimated 1RM           | 60 s           |
| Weighted BOSU lunge jump                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 3 × 15 reps each side  | 30% estimated 1RM           | 70% estimated 1RM           | 30% estimated 1RM           | 60 s           |
| BOSU lateral split squat holding a weight plate                                                                                                                                                                                                                                                                                                                                                                                                                                               | 3 × 15 reps each side  | 30% estimated 1RM           | 70% estimated 1RM           | 30% estimated 1RM           | 60 s           |
| Single-leg weighted calf raise                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 3 × 15 reps each side  | 30% estimated 1RM           | 70% estimated 1RM           | 30% estimated 1RM           | 60 s           |
| Note: 1RM = one-repetition maximum. Estimated 1RM refers to the exercise-specific one-repetition maximum estimated before the intervention. For loaded farmer's walks, intensity was prescribed relative to the maximum load that could be carried for 15 m with correct posture and without stopping. For unilateral exercises, repetitions were completed on each side. In the BFR+LIFT group, cuffs were maintained during the 60-s inter-set rest periods and released between exercises. |                        |                             |                             |                             |                |

BFR+LIFT Intervention Protocol. Participants in the BFR+LIFT group performed blood flow restriction training using a KAATSU Master automatic pneumatic training device and cuffs (Japan). The cuff width was 5 cm, and cuffs were placed bilaterally around the proximal third of the thighs. Cuff pressure was prescribed using an individualized estimated arterial occlusion pressure (AOP) approach [13]. Estimated AOP was calculated from thigh circumference, resting systolic blood pressure (SBP), and resting diastolic blood pressure (DBP) using the following equation:  $AOP \text{ (mmHg)} = 5.893 \times \text{thigh circumference (cm)} + 0.734 \times DBP \text{ (mmHg)} + 0.912 \times SBP \text{ (mmHg)} - 220.046$ . Training pressure was set at 40%-60% of the estimated AOP and was progressively increased across the intervention period according to participant tolerance [14]. The warm-up was performed without cuff inflation. During training, cuffs

were inflated during each exercise block, maintained during the 60-s inter-set rest periods, and released between exercises. Cuff pressure was checked during each session and was slightly reduced if participants reported discomfort. Participants performed the low-intensity functional training protocol at 30% of exercise-specific estimated 1RM, except that loaded farmer's walks were prescribed at 30% of the maximum 15-m carry load. Training was performed three times per week, with three sets for each exercise. Repetition-based exercises were performed for 15 repetitions per set, unilateral exercises were performed for 15 repetitions per side, and loaded farmer's walks were performed over 15 m per set.

**HIFT Intervention Protocol.** Participants in the HIFT group performed the same functional training program at 70% of exercise-specific estimated 1RM, except that loaded farmer's walks were prescribed at 70% of the maximum 15-m carry load, following the preparatory warm-up. Training was performed three times per week, with three sets for each exercise. Repetition-based exercises were performed for 15 repetitions per set, unilateral exercises were performed for 15 repetitions per side, and loaded farmer's walks were performed over 15 m per set. A 60-s rest interval was provided between sets.

**LIFT Intervention Protocol.** Participants in the LIFT group performed the same low-intensity functional training program at 30% of exercise-specific estimated 1RM, except that loaded farmer's walks were prescribed at 30% of the maximum 15-m carry load, following the preparatory warm-up, without BFR. Training was performed three times per week, with three sets for each exercise. Repetition-based exercises were performed for 15 repetitions per set, unilateral exercises were performed for 15 repetitions per side, and loaded farmer's walks were performed over 15 m per set. A 60-s rest interval was provided between sets.

**Testing Procedures.** Participants were instructed to avoid strenuous physical activity for 48 h before each testing session. Baseline testing commenced 5 days before the formal intervention. Three measurements were obtained on days 3, 4, and 5 before the intervention, and the highest value was retained as the pre-intervention result. Post-intervention testing was conducted on days 3, 4, and 5 after a 48-h recovery period following completion of the intervention. Isokinetic strength assessments were performed between 15:00 and 18:30, whereas the remaining badminton-related performance tests were conducted between 13:30 and 14:30. Pre- and post-intervention assessments were performed within the same time windows. The same equipment, testers, testing order, and testing procedures were used throughout the study for each participant. Before formal testing, all participants completed a standardized warm-up and familiarization trials for each assessment. Standardized instructions regarding movement execution were provided, and verbal encouragement was given during testing to ensure maximal effort.

**Isokinetic Strength Assessment.** Lower-limb isokinetic strength was assessed using a Biodex isokinetic dynamometer (Biodex Medical Systems, USA). Hip flexion-extension was tested in a standing position, whereas knee flexion-extension and ankle dorsiflexion-plantarflexion were tested in a seated position. Participants were positioned and stabilized according to standardized procedures and the manufacturer's instructions. The anatomical axis of rotation of each joint was aligned with the dynamometer axis, and straps were used when appropriate to minimize compensatory movements. Both limbs were tested in the same order at baseline and post-intervention. For each joint, participants performed five maximal reciprocal flexion-extension repetitions at an angular velocity of 60°/s. Two trials were completed, and the highest peak torque recorded across all valid repetitions was used for analysis. Relative peak torque was calculated as peak torque divided by body mass and expressed as N·m·kg<sup>-1</sup>.

**Badminton-Related Performance Assessments.** The T-test was used to assess lower-limb agility. Participants started at point A. Upon the start signal, they sprinted to point B and touched the cone with the right hand, then shuffled left to touch the cone at point C with the left hand, shuffled right to touch the cone at point D with the right hand, returned to point B and touched the cone with the left hand, and finally backpedaled to point A to complete the test. After the first trial, participants rested for 5 min before completing a second trial. The better of the 2 performances was used for statistical analysis.

The badminton court lateral change-of-direction test was performed from one doubles sideline. On the start command, participants moved as quickly as possible to the opposite doubles sideline, decelerated with a lunge, and touched the sideline with the racket hand before immediately turning and returning to the starting sideline. One left-right movement cycle was counted as 1 repetition, and a total of 5 repetitions were completed. Total completion time was recorded. After the first trial, participants rested for 5 min before completing a second trial. The better of the 2 performances was used for statistical analysis.

In the badminton court multi-directional "Mi"-shaped movement test, participants started from the center of the badminton court and performed badminton-specific lunge movements in eight directions, touching the corresponding markers with the racket hand. After each touch, they returned to the center of the court before proceeding to the next direction. The test was completed after one full circuit of continuous multidirectional movement in a counterclockwise sequence. After the first trial, participants rested for 5 min

before completing a second trial. The better of the 2 performances was used for statistical analysis. Trials were considered invalid if the participant failed to touch the marker, touched the markers in the wrong order, or did not follow the prescribed procedure, in which case the trial was repeated.

Thirty-meter sprint performance was assessed on a track. Participants adopted a standing start and initiated the sprint voluntarily when ready. Photoelectric timing gates (SWIFT DUO, Australia) were positioned at the start and finish lines, and sprint time was recorded automatically. Two trials were performed, and the fastest time was used for analysis.

**Main Outcome Measures.** The outcomes were organized into three domains: lower-limb isokinetic strength, strength-balance indices, and badminton-related performance. Lower-limb isokinetic strength was assessed using relative peak torque. Strength-balance indices included the agonist-antagonist peak torque ratio and bilateral strength difference. Badminton-related performance included the T-test, badminton court lateral change-of-direction test, badminton court multi-directional "Mi"-shaped movement test, and 30-m sprint.

Strength-balance indices were calculated from relative peak torque values. The agonist-antagonist peak torque ratio (PTR) was calculated as flexor relative peak torque divided by extensor relative peak torque. For the hip, knee, and ankle joints, the ratios were calculated as hip flexor/hip extensor, knee flexor/knee extensor, and ankle dorsiflexor/ankle plantarflexor, respectively. The knee flexor/extensor ratio corresponded to the conventional hamstring-to-quadriceps ratio. Bilateral strength difference, also referred to as quantitative difference (QD), was calculated as  $|\text{left side} - \text{right side}| / \max(\text{left side}, \text{right side})$ , with lower values indicating smaller bilateral asymmetry.

## Statistical analysis

Statistical analyses were performed using SPSS version 27.0 software (IBM Corp., Armonk, NY, USA). Because two participants withdrew during the first week and did not complete post-intervention assessments, all analyses were conducted using complete cases, and missing post-intervention data were not imputed. The Shapiro-Wilk test was used to assess the normality of pre- and post-intervention values within each group. Normally distributed data were presented as mean  $\pm$  standard deviation, whereas non-normally distributed data were presented as median and interquartile range [M (P25, P75)]. For within-group comparisons, paired differences were calculated as post-intervention value minus pre-intervention value, and the normality of paired differences was assessed using the Shapiro-Wilk test. If the paired differences were normally distributed, paired-samples t tests were used to compare pre- and post-intervention values; otherwise, Wilcoxon signed-rank tests were used. These within-group analyses were used to describe pre- to post-intervention changes within each training condition and were not used as the primary basis for between-group inference. Effect sizes were calculated according to the statistical test used: Cohen's  $d_z$  was calculated for paired-samples t tests, whereas effect size  $r$  was calculated and converted to an equivalent Cohen's  $d$  for Wilcoxon signed-rank tests. The main between-group inference for intervention effects was based on change rates. Because no significant between-group differences were observed in baseline characteristics or pre-intervention outcome measures, change-rate comparisons were used to evaluate the magnitude of training-induced adaptations among groups. The change rate for each variable was calculated as  $[(\text{post-intervention value} - \text{pre-intervention value}) / \text{pre-intervention value}] \times 100$  and expressed as a percentage. For timed performance tests and bilateral-difference variables, lower values indicated better performance or smaller asymmetry; therefore, negative change rates represented improvement. Homogeneity of variance for change-rate data across the three groups was assessed using Levene's test. If the assumption of equal variances was satisfied, one-way analysis of variance was performed; otherwise, Brown-Forsythe ANOVA was used. For variables showing significant overall between-group differences, post hoc multiple comparisons were conducted using Tukey's honestly significant difference test when variances were equal and the Games-Howell test when variances were unequal. All tests were two-tailed, and  $P < 0.05$  was considered statistically significant. Because multiple strength, strength-balance, and sport-specific performance outcomes were examined, the findings were interpreted by outcome domain, with emphasis placed on consistent patterns across related variables rather than isolated significant results.

## Results

### Participant flow, adherence, and baseline characteristics

A total of 48 amateur badminton players were randomized to the BFR+LIFT, HIFT, or LIFT groups. Two participants withdrew during the first week for scheduling reasons unrelated to the intervention, including one participant in the BFR+LIFT group and one in the HIFT

group. Therefore, 46 participants completed post-intervention testing and were included in the complete-case analysis. All participants who completed the study attended all 24 supervised training sessions, and no training-related adverse events were reported. Participant flow, including recruitment, randomization, attrition, and complete-case analysis, is shown in Fig. 1.

Baseline characteristics were comparable among groups (Table 2). No significant between-group differences were observed in pre-intervention strength, muscle strength balance, or badminton-related performance outcomes, indicating that the groups were comparable before the intervention.

Table 2  
Baseline characteristics of participants

| Group                                                                                                                                                                                                                                       | N (Male/Female) | Age (years)  | Height (m)  | Body mass (kg) | Badminton rating | Weekly playing frequency |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|--------------|-------------|----------------|------------------|--------------------------|
| BFR+LIFT                                                                                                                                                                                                                                    | 15 (11/4)       | 22.67 ± 1.95 | 1.73 ± 0.06 | 70.98 ± 11.45  | 4.07 ± 0.82      | 3.67 ± 1.54              |
| HIFT                                                                                                                                                                                                                                        | 15 (10/5)       | 22.40 ± 1.30 | 1.75 ± 0.08 | 71.22 ± 13.48  | 4.17 ± 0.59      | 3.60 ± 1.76              |
| LIFT                                                                                                                                                                                                                                        | 16 (10/6)       | 22.25 ± 2.05 | 1.70 ± 0.08 | 68.04 ± 14.74  | 4.22 ± 0.66      | 4.25 ± 1.84              |
| p value                                                                                                                                                                                                                                     | 0.923           | 0.811        | 0.242       | 0.760          | 0.827            | 0.516                    |
| Note: Values are presented as mean ± SD unless otherwise indicated. BFR+LIFT = blood flow restriction combined with low-intensity functional training; HIFT = high-intensity functional training; LIFT = low-intensity functional training. |                 |              |             |                |                  |                          |

## Effects on lower-limb isokinetic strength

Pre- to post-intervention changes in lower-limb isokinetic relative peak torque are presented in Table 3. In the BFR+LIFT group, significant increases were observed in left and right hip flexion, left and right hip extension, left and right knee extension, left and right knee flexion, and left and right ankle plantarflexion relative peak torque. No significant changes were observed in left or right ankle dorsiflexion relative peak torque.

The HIFT group showed a similar strength-adaptation pattern, with significant improvements in left and right hip flexion, left and right hip extension, left and right knee extension, left and right knee flexion, and left and right ankle plantarflexion relative peak torque, but not in ankle dorsiflexion. In contrast, the LIFT group showed significant increases only in left and right knee extension and left and right ankle plantarflexion relative peak torque, with no significant changes in hip strength, knee flexion strength, or ankle dorsiflexion strength.

Between-group comparisons of change rates showed significant group effects for all hip strength outcomes, all knee strength outcomes, and left and right ankle plantarflexion relative peak torque. Post hoc comparisons indicated that both BFR+LIFT and HIFT produced greater improvements than LIFT in hip flexion, hip extension, right knee extension, and ankle plantarflexion outcomes. For left knee extension, HIFT improved more than LIFT; for left knee flexion, BFR+LIFT improved more than LIFT. Right knee flexion showed a significant overall group effect, but no adjusted pairwise post hoc comparison reached statistical significance. The distribution of individual change rates for the key strength outcomes is shown in Fig. 2.

Table 3  
Changes in lower-limb isokinetic relative peak torque

| Domain                         | Outcome                                   | BFR+LIFT<br>pre → post<br>(within p; d)              | BFR+LIFT<br>Δ% | HIFT<br>pre → post<br>(within p;<br>d)               | HIFT<br>Δ%    | LIFT<br>pre → post<br>(within p;<br>d)                      | LIFT<br>Δ%   | Group<br>p | Significant<br>post hoc                              |
|--------------------------------|-------------------------------------------|------------------------------------------------------|----------------|------------------------------------------------------|---------------|-------------------------------------------------------------|--------------|------------|------------------------------------------------------|
| Lower-limb isokinetic strength | Left hip flexion relative peak torque     | 1.204 ± 0.345 → 1.529 ± 0.388 (p = 0.003; d = 0.908) | 30.63 ± 31.79  | 1.109 ± 0.271 → 1.289 ± 0.228 (p = 0.003; d = 0.940) | 20.27 ± 27.11 | 1.166 ± 0.339 → 1.175 ± 0.330 (p = 0.108; d = 0.428)        | 1.04 ± 2.08  | 0.007      | BFR+LIFT > LIFT (p = 0.008); HIFT > LIFT (p = 0.040) |
| Lower-limb isokinetic strength | Right hip flexion relative peak torque    | 1.277 ± 0.332 → 1.511 ± 0.382 (p = 0.003; d = 0.926) | 20.39 ± 21.22  | 1.130 ± 0.304 → 1.311 ± 0.239 (p = 0.003; d = 0.913) | 20.21 ± 24.03 | 1.294 ± 0.260 → 1.297 ± 0.256 (p = 0.716; d = 0.093)        | 0.31 ± 2.31  | 0.007      | BFR+LIFT > LIFT (p = 0.007); HIFT > LIFT (p = 0.016) |
| Lower-limb isokinetic strength | Left hip extension relative peak torque   | 1.571 ± 0.427 → 2.101 ± 0.528 (p = 0.003; d = 0.936) | 39.22 ± 42.10  | 1.544 ± 0.440 → 2.014 ± 0.471 (p = 0.001; d = 3.046) | 36.92 ± 42.20 | 1.525 ± 0.324 → 1.604 ± 0.308 (p = 0.061; d = 0.506)        | 5.98 ± 11.28 | 0.022      | BFR+LIFT > LIFT (p = 0.024); HIFT > LIFT (p = 0.036) |
| Lower-limb isokinetic strength | Right hip extension relative peak torque  | 1.720 ± 0.315 → 2.308 ± 0.724 (p = 0.002; d = 0.972) | 34.22 ± 34.92  | 1.734 ± 0.488 → 2.268 ± 0.640 (p = 0.003; d = 0.931) | 35.51 ± 38.36 | 1.794 ± 0.301 → 1.889 ± 0.306 (p = 0.089; d = 0.454)        | 6.12 ± 13.00 | 0.019      | BFR+LIFT > LIFT (p = 0.023); HIFT > LIFT (p = 0.030) |
| Lower-limb isokinetic strength | Left knee extension relative peak torque  | 1.278 ± 0.445 → 1.425 ± 0.466 (p < 0.001; d = 1.089) | 12.54 ± 9.39   | 1.376 ± 0.650 → 1.576 ± 0.740 (p < 0.001; d = 1.192) | 15.12 ± 11.37 | 1.294 ± 0.482 → 1.186 (1.016, 1.554) (p = 0.025; d = 0.622) | 4.95 ± 6.35  | 0.010      | HIFT > LIFT (p = 0.010)                              |
| Lower-limb isokinetic strength | Right knee extension relative peak torque | 1.396 ± 0.486 → 1.552 ± 0.574 (p = 0.001; d = 1.026) | 10.77 ± 9.25   | 1.304 ± 0.534 → 1.509 ± 0.588 (p = 0.001; d = 1.030) | 17.70 ± 16.77 | 1.363 ± 0.525 → 1.407 ± 0.538 (p = 0.008; d = 1.754)        | 3.47 ± 3.58  | 0.007      | BFR+LIFT > LIFT (p = 0.027); HIFT > LIFT (p = 0.015) |
| Lower-limb isokinetic strength | Left knee flexion relative peak torque    | 0.618 ± 0.188 → 0.864 ± 0.275 (p < 0.001; d = 1.198) | 43.24 ± 32.89  | 0.721 ± 0.295 → 0.927 ± 0.415 (p < 0.001; d = 1.137) | 27.58 ± 20.45 | 0.647 (0.547, 0.791) → 0.734 ± 0.225 (p = 0.425; d = 0.205) | 6.00 ± 23.98 | 0.001      | BFR+LIFT > LIFT (p < 0.001)                          |

Note: Values are presented as mean ± SD or median (P25, P75), according to distribution. d = within-group effect size. Δ% = (post-test – pre-test) / pre-test × 100. Group p values are based on change-rate comparisons. For significant overall group effects, post hoc results are shown after Tukey HSD or Games-Howell adjustment. BFR+LIFT = blood flow restriction combined with low-intensity functional training; HIFT = high-intensity functional training; LIFT = low-intensity functional training.

| Domain                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Outcome                                         | BFR+LIFT<br>pre → post<br>(within p; d)                     | BFR+LIFT<br>Δ% | HIFT<br>pre → post<br>(within p; d)                         | HIFT<br>Δ%    | LIFT<br>pre → post<br>(within p; d)                         | LIFT<br>Δ%   | Group<br>p | Significant<br>post hoc                              |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|-------------------------------------------------------------|----------------|-------------------------------------------------------------|---------------|-------------------------------------------------------------|--------------|------------|------------------------------------------------------|
| Lower-limb isokinetic strength                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Right knee flexion relative peak torque         | 0.712 ± 0.226 → 0.905 ± 0.330 (p < 0.001; d = 1.101)        | 27.84 ± 21.32  | 0.748 ± 0.252 → 0.983 ± 0.445 (p = 0.005; d = 0.854)        | 28.98 ± 30.34 | 0.758 ± 0.222 → 0.789 ± 0.244 (p = 0.515; d = 0.167)        | 6.70 ± 24.82 | 0.032      | No significant pairwise difference                   |
| Lower-limb isokinetic strength                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Left ankle plantarflexion relative peak torque  | 0.487 ± 0.174 → 0.655 ± 0.239 (p < 0.001; d = 2.272)        | 35.54 ± 11.63  | 0.531 ± 0.288 → 0.588 (0.484, 0.790) (p < 0.001; d = 3.451) | 33.25 ± 17.00 | 0.501 ± 0.143 → 0.532 ± 0.150 (p = 0.015; d = 0.683)        | 6.58 ± 9.06  | < 0.001    | BFR+LIFT > LIFT (p < 0.001); HIFT > LIFT (p < 0.001) |
| Lower-limb isokinetic strength                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Right ankle plantarflexion relative peak torque | 0.503 ± 0.197 → 0.675 ± 0.231 (p < 0.001; d = 3.703)        | 38.34 ± 20.23  | 0.447 ± 0.182 → 0.634 ± 0.308 (p < 0.001; d = 3.703)        | 38.66 ± 16.98 | 0.468 ± 0.177 → 0.498 ± 0.186 (p = 0.002; d = 0.930)        | 6.70 ± 6.86  | < 0.001    | BFR+LIFT > LIFT (p < 0.001); HIFT > LIFT (p < 0.001) |
| Lower-limb isokinetic strength                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Left ankle dorsiflexion relative peak torque    | 0.361 ± 0.098 → 0.392 ± 0.130 (p = 0.072; d = 0.503)        | 8.03 ± 17.23   | 0.332 (0.295, 0.392) → 0.369 ± 0.113 (p = 0.445; d = 0.203) | 3.06 ± 16.27  | 0.374 ± 0.127 → 0.386 ± 0.147 (p = 0.460; d = 0.190)        | 2.58 ± 14.17 | 0.582      | None                                                 |
| Lower-limb isokinetic strength                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Right ankle dorsiflexion relative peak torque   | 0.361 (0.301, 0.408) → 0.405 ± 0.125 (p = 0.080; d = 0.487) | 8.23 ± 16.20   | 0.352 ± 0.101 → 0.379 ± 0.123 (p = 0.173; d = 0.752)        | 7.59 ± 20.66  | 0.395 ± 0.141 → 0.352 (0.260, 0.605) (p = 0.603; d = 0.133) | 1.16 ± 20.73 | 0.532      | None                                                 |
| Note: Values are presented as mean ± SD or median (P25, P75), according to distribution. d = within-group effect size. Δ% = (post-test – pre-test) / pre-test × 100. Group p values are based on change-rate comparisons. For significant overall group effects, post hoc results are shown after Tukey HSD or Games-Howell adjustment. BFR+LIFT = blood flow restriction combined with low-intensity functional training; HIFT = high-intensity functional training; LIFT = low-intensity functional training. |                                                 |                                                             |                |                                                             |               |                                                             |              |            |                                                      |

## Effects on muscle strength balance

Changes in muscle strength balance outcomes are presented in Table 4. In the BFR+LIFT group, significant improvements were observed in hip flexion bilateral difference, left and right knee flexion/extension ratios, knee flexion bilateral difference, and left and right ankle dorsiflexion/plantarflexion ratios. No significant changes were observed in the remaining hip, knee, or ankle muscle strength balance outcomes.

In the HIFT group, significant changes were observed only in the left and right ankle dorsiflexion/plantarflexion ratios. The LIFT group showed no significant pre- to post-intervention changes in any muscle strength balance outcome.

Between-group comparisons showed significant group effects for the left knee flexion/extension ratio, knee flexion bilateral difference, and left and right ankle dorsiflexion/plantarflexion ratios. Post hoc comparisons indicated that BFR+LIFT produced a greater increase in the left knee flexion/extension ratio than LIFT. For knee flexion bilateral difference, BFR+LIFT showed a greater reduction than both

HIFT and LIFT. For the left ankle dorsiflexion/plantarflexion ratio, both BFR+LIFT and HIFT showed greater reductions than LIFT, whereas for the right ankle dorsiflexion/plantarflexion ratio, HIFT showed a greater reduction than LIFT. The distribution of individual change rates for these muscle strength-balance outcomes is shown in Fig. 3.

Table 4  
Changes in muscle strength balance outcomes

| Domain                  | Outcome                            | BFR+LIFT<br>pre →<br>post<br>(within p;<br>d)        | BFR+LIFT<br>Δ% | HIFT<br>pre →<br>post<br>(within<br>p; d)                   | HIFT<br>Δ%      | LIFT<br>pre →<br>post<br>(within<br>p; d)                          | LIFT<br>Δ%    | Group<br>p | Significant<br>post hoc     |
|-------------------------|------------------------------------|------------------------------------------------------|----------------|-------------------------------------------------------------|-----------------|--------------------------------------------------------------------|---------------|------------|-----------------------------|
| Muscle strength balance | Left hip flexion/extension ratio   | 0.770 ± 0.104 → 0.734 ± 0.103 (p = 0.064; d = 0.520) | -4.43 ± 8.65   | 0.732 ± 0.127 → 0.654 (0.537, 0.758) (p = 0.058; d = 0.532) | -8.85 ± 16.44   | 0.761 ± 0.121 → 0.730 ± 0.121 (p = 0.078; d = 0.474)               | -3.76 ± 9.37  | 0.449      | None                        |
| Muscle strength balance | Right hip flexion/extension ratio  | 0.738 ± 0.104 → 0.679 ± 0.141 (p = 0.109; d = 0.442) | -7.31 ± 17.40  | 0.662 ± 0.126 → 0.601 ± 0.136 (p = 0.140; d = 0.825)        | -7.65 ± 18.36   | 0.724 ± 0.096 → 0.690 ± 0.108 (p = 0.063; d = 0.501)               | -4.41 ± 9.55  | 0.814      | None                        |
| Muscle strength balance | Hip flexion bilateral difference   | 0.142 ± 0.104 → 0.051 ± 0.033 (p = 0.004; d = 0.901) | -41.63 ± 53.30 | 0.171 ± 0.141 → 0.105 ± 0.077 (p = 0.118; d = 0.430)        | 47.07 ± 204.23  | 0.127 (0.032, 0.214) → 0.109 (0.044, 0.191) (p = 0.168; d = 0.362) | 12.99 ± 35.67 | 0.174      | None                        |
| Muscle strength balance | Hip extension bilateral difference | 0.153 ± 0.126 → 0.106 ± 0.075 (p = 0.237; d = 0.319) | 93.60 ± 244.90 | 0.101 (0.042, 0.229) → 0.139 ± 0.091 (p = 0.838; d = 0.054) | 103.04 ± 233.73 | 0.167 ± 0.096 → 0.161 ± 0.083 (p = 0.693; d = 0.101)               | 3.00 ± 41.84  | 0.311      | None                        |
| Muscle strength balance | Left knee flexion/extension ratio  | 0.500 ± 0.084 → 0.633 ± 0.146 (p = 0.003; d = 0.938) | 28.31 ± 30.83  | 0.535 (0.492, 0.577) → 0.603 ± 0.127 (p = 0.069; d = 1.063) | 12.21 ± 22.07   | 0.562 ± 0.085 → 0.567 ± 0.143 (p = 0.879; d = 0.039)               | 1.45 ± 24.29  | 0.022      | BFR+LIFT > LIFT (p = 0.017) |

Note: Values are presented as mean ± SD or median (P25, P75), according to distribution. d = within-group effect size. Δ% = (post-test - pre-test) / pre-test × 100. Negative Δ% for bilateral-difference variables indicates reduced asymmetry. For dorsiflexion/plantarflexion ratio outcomes, negative Δ% reflects a lower ratio after training. Group p values are based on change-rate comparisons. BFR+LIFT = blood flow restriction combined with low-intensity functional training; HIFT = high-intensity functional training; LIFT = low-intensity functional training.

| Domain                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Outcome                                       | BFR+LIFT<br>pre →<br>post<br>(within p;<br>d)               | BFR+LIFT<br>Δ% | HIFT<br>pre →<br>post<br>(within<br>p; d)                          | HIFT<br>Δ%     | LIFT<br>pre →<br>post<br>(within<br>p; d)                   | LIFT<br>Δ%    | Group<br>p | Significant<br>post hoc                                  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------|-------------------------------------------------------------|----------------|--------------------------------------------------------------------|----------------|-------------------------------------------------------------|---------------|------------|----------------------------------------------------------|
| Muscle strength balance                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Right knee flexion/extension ratio            | 0.520 ± 0.059 → 0.614 ± 0.174 (p = 0.023; d = 0.661)        | 16.97 ± 25.76  | 0.531 (0.518, 0.663) → 0.656 ± 0.150 (p = 0.324; d = 0.264)        | 12.68 ± 33.52  | 0.582 ± 0.095 → 0.511 (0.486, 0.783) (p = 0.646; d = 0.117) | 3.20 ± 24.45  | 0.384      | None                                                     |
| Muscle strength balance                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Knee extension bilateral difference           | 0.180 ± 0.107 → 0.168 ± 0.103 (p = 0.106; d = 0.446)        | -3.95 ± 17.17  | 0.156 (0.123, 0.203) → 0.177 ± 0.095 (p = 0.286; d = 0.286)        | -0.21 ± 18.00  | 0.249 ± 0.141 → 0.241 ± 0.133 (p = 0.517; d = 0.166)        | 5.44 ± 62.92  | 0.804      | None                                                     |
| Muscle strength balance                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Knee flexion bilateral difference             | 0.180 ± 0.121 → 0.055 (0.013, 0.117) (p < 0.001; d = 3.703) | -59.47 ± 25.53 | 0.081 (0.032, 0.121) → 0.064 (0.041, 0.182) (p = 0.922; d = 0.026) | 42.40 ± 119.57 | 0.183 ± 0.151 → 0.110 (0.037, 0.173) (p = 0.438; d = 0.395) | -7.33 ± 56.00 | 0.007      | BFR+LIFT < HIFT (p = 0.014); BFR+LIFT < LIFT (p = 0.008) |
| Muscle strength balance                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Left ankle dorsiflexion/plantarflexion ratio  | 0.793 (0.604, 0.930) → 0.635 ± 0.175 (p < 0.001; d = 3.235) | -19.54 ± 14.92 | 0.814 ± 0.349 → 0.606 ± 0.196 (p = 0.002; d = 1.009)               | -21.16 ± 17.30 | 0.783 ± 0.261 → 0.732 ± 0.183 (p = 0.173; d = 0.358)        | -2.86 ± 16.70 | 0.005      | BFR+LIFT < LIFT (p = 0.018); HIFT < LIFT (p = 0.009)     |
| Muscle strength balance                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Right ankle dorsiflexion/plantarflexion ratio | 0.870 ± 0.416 → 0.644 ± 0.210 (p = 0.003; d = 2.471)        | -19.69 ± 18.86 | 0.863 ± 0.270 → 0.661 ± 0.195 (p < 0.001; d = 1.496)               | -22.19 ± 12.23 | 0.910 ± 0.308 → 0.933 (0.852, 0.960) (p = 0.185; d = 0.347) | -4.42 ± 23.30 | 0.024      | HIFT < LIFT (p = 0.031)                                  |
| Muscle strength                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Ankle plantarflexion bilateral difference     | 0.205 ± 0.155 →                                             | 24.00 ± 117.11 | 0.169 ±                                                            | 42.09 ±        | 0.216 ±                                                     | 219.58 ±      | 0.191      | None                                                     |
| Note: Values are presented as mean ± SD or median (P25, P75), according to distribution. d = within-group effect size. Δ% = (post-test – pre-test) / pre-test × 100. Negative Δ% for bilateral-difference variables indicates reduced asymmetry. For dorsiflexion/plantarflexion ratio outcomes, negative Δ% reflects a lower ratio after training. Group p values are based on change-rate comparisons. BFR+LIFT = blood flow restriction combined with low-intensity functional training; HIFT = high-intensity functional training; LIFT = low-intensity functional training. |                                               |                                                             |                |                                                                    |                |                                                             |               |            |                                                          |

| Domain                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Outcome                                    | BFR+LIFT<br>pre →<br>post<br>(within p;<br>d)                       | BFR+LIFT<br>Δ%    | HIFT<br>pre →<br>post<br>(within<br>p; d)                                                        | HIFT<br>Δ%           | LIFT<br>pre →<br>post<br>(within<br>p; d)                                                        | LIFT<br>Δ%      | Group<br>p | Significant<br>post hoc |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------|---------------------------------------------------------------------|-------------------|--------------------------------------------------------------------------------------------------|----------------------|--------------------------------------------------------------------------------------------------|-----------------|------------|-------------------------|
| balance                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                            | 0.128<br>(0.056,<br>0.265) (p<br>= 0.129;<br>d = 0.416)             |                   | 0.107<br>→<br>0.132<br>±<br>0.073<br>(p =<br>0.164;<br>d =<br>0.379)                             | 157.14               | 0.167<br>→<br>0.212<br>±<br>0.154<br>(p =<br>0.834;<br>d =<br>0.054)                             | 520.20          |            |                         |
| Muscle<br>strength<br>balance                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Ankle dorsiflexion<br>bilateral difference | 0.146 ±<br>0.071 →<br>0.124 ±<br>0.097 (p<br>= 0.255;<br>d = 0.307) | -12.09 ±<br>44.68 | 0.069<br>(0.031,<br>0.126)<br>→<br>0.054<br>(0.029,<br>0.094)<br>(p =<br>0.538;<br>d =<br>0.163) | 42.64<br>±<br>156.10 | 0.106<br>(0.077,<br>0.156)<br>→<br>0.106<br>(0.060,<br>0.209)<br>(p =<br>0.630;<br>d =<br>0.123) | 4.33 ±<br>62.19 | 0.330      | None                    |
| Note: Values are presented as mean ± SD or median (P25, P75), according to distribution. d = within-group effect size. Δ% = (post-test – pre-test) / pre-test × 100. Negative Δ% for bilateral-difference variables indicates reduced asymmetry. For dorsiflexion/plantarflexion ratio outcomes, negative Δ% reflects a lower ratio after training. Group p values are based on change-rate comparisons. BFR+LIFT = blood flow restriction combined with low-intensity functional training; HIFT = high-intensity functional training; LIFT = low-intensity functional training. |                                            |                                                                     |                   |                                                                                                  |                      |                                                                                                  |                 |            |                         |

## Effects on badminton-related performance

Changes in badminton-related performance outcomes are presented in Table 5. The BFR+LIFT group showed significant improvements in all four performance tests, as indicated by reduced completion times in the T-test, badminton court lateral change-of-direction test, badminton court multi-directional "Mi"-shaped movement test, and 30-m sprint. The HIFT group showed significant improvements in the badminton court lateral change-of-direction test and 30-m sprint, whereas changes in the T-test and "Mi"-shaped movement test did not reach statistical significance. The LIFT group showed no significant changes in any badminton-related performance outcome.

Between-group comparisons showed that only the 30-m sprint demonstrated a significant group effect. Post hoc analysis indicated that the reduction in 30-m sprint time was greater in the BFR+LIFT group than in the LIFT group. No significant between-group differences were observed for the T-test, badminton court lateral change-of-direction test, or badminton court multi-directional "Mi"-shaped movement test. Individual change-rate distributions for badminton-related performance outcomes are shown in Fig. 4.

Table 5  
Changes in badminton-related performance outcomes

| Domain                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Outcome                                                     | BFR+LIFT<br>pre → post<br>(within p; d)                            | BFR+LIFT<br>Δ% | HIFT<br>pre → post<br>(within p;<br>d)                          | HIFT<br>Δ%   | LIFT<br>pre → post<br>(within p;<br>d)                                   | LIFT<br>Δ%   | Group<br>p | Significant<br>post hoc     |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------|--------------------------------------------------------------------|----------------|-----------------------------------------------------------------|--------------|--------------------------------------------------------------------------|--------------|------------|-----------------------------|
| Badminton-related performance                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | T-test                                                      | 13.660 ± 0.957 → 13.221 ± 0.940 (p = 0.034; d = 0.606)             | -3.09 ± 5.30   | 13.363 ± 1.059 → 12.840 (12.250, 13.420) (p = 0.080; d = 0.488) | -2.61 ± 5.24 | 13.191 ± 0.952 → 13.052 ± 1.064 (p = 0.394; d = 0.220)                   | -1.01 ± 4.76 | 0.497      | None                        |
| Badminton-related performance                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Badminton court lateral change-of-direction test            | 16.693 ± 1.058 → 16.156 ± 1.169 (p = 0.035; d = 0.602)             | -3.14 ± 5.27   | 16.533 ± 1.172 → 16.099 ± 1.194 (p = 0.034; d = 0.606)          | -2.56 ± 4.29 | 16.358 ± 1.027 → 16.196 ± 1.457 (p = 0.520; d = 0.165)                   | -1.01 ± 6.03 | 0.512      | None                        |
| Badminton-related performance                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Badminton court multi-directional "Mi"-shaped movement test | 22.686 ± 1.627 → 21.506 ± 1.747 (p = 0.016; d = 0.709)             | -5.01 ± 7.27   | 23.310 ± 1.721 → 22.668 ± 2.622 (p = 0.076; d = 0.495)          | -2.96 ± 5.75 | 22.955 (22.450, 25.215) → 22.970 (22.350, 24.852) (p = 0.146; d = 0.383) | -0.50 ± 1.44 | 0.087      | None                        |
| Badminton-related performance                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 30-m sprint                                                 | 5.150 (5.025, 5.510) → 5.060 (4.855, 5.535) (p = 0.013; d = 0.735) | -1.97 ± 2.67   | 5.267 ± 0.413 → 5.214 ± 0.439 (p = 0.017; d = 1.566)            | -1.05 ± 1.58 | 5.115 (4.960, 5.370) → 5.115 (4.970, 5.357) (p = 0.759; d = 0.195)       | -0.07 ± 0.40 | 0.026      | BFR+LIFT < LIFT (p = 0.039) |
| Note: Values are presented as mean ± SD or median (P25, P75), according to distribution. d = within-group effect size. Δ% = (post-test - pre-test) / pre-test × 100. For timed performance tests, negative Δ% indicates faster completion time and therefore improved performance. Group p values are based on change-rate comparisons. BFR+LIFT = blood flow restriction combined with low-intensity functional training; HIFT = high-intensity functional training; LIFT = low-intensity functional training. |                                                             |                                                                    |                |                                                                 |              |                                                                          |              |            |                             |

## Summary of main findings

In summary, BFR+LIFT and HIFT produced broadly comparable improvements in lower-limb isokinetic strength, and both were generally superior to LIFT across the main hip, knee, and ankle plantarflexion outcomes. The effects on muscle strength balance were more selective: BFR+LIFT showed favorable adaptations in knee flexion bilateral difference and knee flexion/extension ratio, whereas both BFR+LIFT and HIFT improved ankle dorsiflexion/plantarflexion ratio outcomes. For badminton-related performance, BFR+LIFT showed the broadest within-group improvement pattern, but clear between-group superiority was observed only for 30-m sprint performance.

## Discussion

The present study compared the effects of 8 weeks of blood flow restriction combined with low-intensity functional training (BFR+LIFT), high-intensity functional training (HIFT), and low-intensity functional training (LIFT) on lower-limb relative peak torque, muscle strength balance, and badminton-related performance in amateur badminton players. Overall, both BFR+LIFT and HIFT improved relative peak torque across several hip, knee, and ankle outcomes, indicating that low-intensity functional training combined with blood flow restriction was able to induce lower-limb strength adaptations comparable to those achieved with high-intensity functional training in the present sample. Compared with general strength gains, the effects of BFR+LIFT on muscle strength balance appeared more selective, mainly reflected by a reduction in knee flexor bilateral difference and an increase in the left knee flexion-to-

extension ratio. In addition, changes in the ankle dorsiflexion-to-plantarflexion ratio indicated altered ankle flexor–extensor strength balance in both the BFR+LIFT and HIFT groups.

For badminton-related performance, the BFR+LIFT group showed a broader range of within-group improvements; however, the clearest between-group advantage was observed only for 30-m sprint performance. More complex badminton-related movement tasks, including the T-test agility test, badminton court lateral change-of-direction test, and badminton court multi-directional “Mi”-shaped movement test, did not show significant between-group differences. Taken together, these findings indicate that BFR+LIFT can induce lower-limb strength gains comparable to HIFT under a lower external load, show selective advantages in some knee-related muscle strength balance outcomes, and produce a clearer improvement in 30-m sprint performance compared with LIFT.

These findings should be interpreted in the context of badminton-specific movement demands. Badminton involves frequent lower-limb actions such as rapid initiation, sudden stopping, lunging, jumping, changing direction, and returning to the center of the court after stroke execution. Among these actions, lunging is one of the most typical footwork patterns in badminton. Mei et al [15]. showed that the forehand lunge places high demands on lower-limb joint control and braking ability. Huang et al [16]. also observed lower-limb muscle strength imbalance in badminton players, providing sport-specific support for including muscle strength balance as an important outcome in the present study. Therefore, in amateur badminton players, improvements in lower-limb strength and muscle strength balance should not be regarded merely as general physical adaptations, but rather as foundational training adaptations that support badminton-specific tasks such as rapid initiation, lunging, changing direction, and multidirectional movement.

With respect to lower-limb strength, the present study showed that the BFR+LIFT group achieved overall improvements in hip, knee, and ankle plantarflexion relative peak torque that were generally comparable to those observed in the HIFT group, despite using only a 30% 1RM external load. In contrast, the LIFT group improved only in a limited number of outcomes, suggesting that low-intensity functional training alone may provide insufficient stimulation for comprehensive lower-limb strength adaptations. This interpretation is consistent with Chen et al [17]., who reported that high-intensity functional training tends to produce broader improvements in physical qualities, physiological function, and body composition than traditional single-mode training. These findings suggest that low-intensity functional training alone may be insufficient to induce comprehensive lower-limb strength adaptations, whereas adding blood flow restriction to low-intensity functional training may enhance the training effect by increasing the internal physiological stimulus. Similar findings have been reported in previous studies combining BFR with functional training. Lv et al [18]. found that low-load functional training combined with BFR and high-load functional training both significantly improved knee extensor and knee flexor peak torque in soccer players, with no clear difference between the two training approaches. In the context of badminton-specific movement demands, the observed improvements in hip, knee, and ankle plantarflexion strength may contribute to coordinated force production across the lower-limb kinetic chain during rapid initiation, lunging, push-off, change of direction, and re-acceleration. Thus, the present findings further indicate that BFR+LIFT can improve lower-limb strength under a low external load, and that these adaptations may provide a strength foundation for multi-joint, coordinated badminton-specific movement tasks in amateur players.

From a mechanistic perspective, the relatively large strength gains observed in the BFR+LIFT group under a low external load may be attributed to the combined effects of neuromuscular stimulation from functional training and the internal physiological load induced by BFR. Functional training emphasizes multi-joint coordination, unstable support conditions, and movement-specific control, which may contribute to strength gains by improving motor unit recruitment efficiency, intermuscular coordination, and movement control. However, low-intensity functional training alone may provide limited stimulation for high-threshold motor unit recruitment and muscle morphological adaptation, which may explain why the LIFT group improved only in a small number of strength outcomes. By contrast, BFR can increase motor unit involvement under a low external load through local hypoxia, metabolite accumulation, and stimulation of group III and IV afferent nerves, thereby facilitating the recruitment of fast-twitch muscle fibers [19, 20]. In addition, BFR may promote muscular adaptation through cell swelling, activation of mTORC1 signaling, increased muscle protein synthesis, elevated growth hormone secretion, and downregulation of myostatin expression [21, 22, 23, 24, 25]. Lixandrão et al [26]. reported that low-load BFR training can induce hypertrophic adaptations comparable to those achieved with high-load resistance training, although maximal strength gains are generally slightly lower than those observed after high-load training. Therefore, the strength improvements induced by BFR+LIFT in the present study may have resulted from the combination of functional movement-control demands under a low external load and the higher internal physiological stimulus induced by BFR, allowing BFR+LIFT to produce isokinetic strength gains comparable to HIFT.

Beyond absolute strength gains, an important finding of the present study was the selective effect of BFR+LIFT on muscle strength balance. Based on the intra-limb and inter-limb muscle strength balance framework proposed by Nie et al [2]., the present study

evaluated lower-limb muscle strength balance from two perspectives: bilateral difference and agonist-to-antagonist ratio. The results showed that the BFR+LIFT group demonstrated within-group improvements in hip flexion bilateral difference, knee flexion bilateral difference, bilateral knee flexion-to-extension ratios, and bilateral ankle dorsiflexion-to-plantarflexion ratios. However, between-group comparisons indicated that the clear advantages of BFR+LIFT were mainly concentrated in the reduction of knee flexor bilateral difference and the increase in the left knee flexion-to-extension ratio. These findings suggest that absolute strength gains and optimization of muscle strength balance do not necessarily occur in parallel. High-intensity training can effectively increase force output, but it does not necessarily correct pre-existing asymmetrical strength patterns. In contrast, BFR+LIFT improve force output while exerting a more favorable influence on force distribution and coordination between the knee flexor and extensor muscle groups. In addition, changes in the ankle dorsiflexion-to-plantarflexion ratio appeared to reflect a common adaptation in both the BFR+LIFT and HIFT groups, rather than a unique advantage of BFR+LIFT.

The functional training content itself provided an important training basis for improvements in muscle strength balance. All three groups performed exercises involving unilateral support, multi-joint coordination, and core stability, which are consistent with theoretical pathways for improving bilateral force distribution, force transmission, and movement control. Nie et al [2]. suggested that unilateral strength training and core training can improve muscle strength balance by enhancing neuromuscular coordination, optimizing force transmission, and improving movement control. Yin et al [27]. also reported that 12 weeks of lower-limb functional training improved ipsilateral knee flexion-to-extension strength ratios and reduced side-to-side strength imbalance around the lower-limb joints in rhythmic gymnasts. Compared with HIFT and LIFT, BFR+LIFT produced clearer improvements in knee flexor bilateral difference and the left knee flexion-to-extension ratio, suggesting that its advantage may not be attributable solely to the functional training exercises themselves, but may also be related to the combined effects of movement-control demands under a low external load and the internal physiological load induced by blood flow restriction. The lower external load may help reduce compensatory movements under high-load conditions and allow greater involvement of the weaker side or relatively under-activated muscle groups. At the same time, the local metabolic stress and neuromuscular recruitment stimulus induced by BFR may further amplify the effects of low-load training on force distribution and agonist–antagonist coordination.

Among the specific muscle strength balance outcomes, the improvement in the knee flexion-to-extension ratio after BFR+LIFT deserves particular attention. The knee flexion-to-extension ratio, also referred to as the hamstring-to-quadriceps ratio, reflects the strength relationship between the hamstrings and quadriceps within the same knee joint and is an important indicator of agonist–antagonist muscle balance around the knee. Ruas et al [28]. suggested that the hamstring-to-quadriceps ratio can be used to describe the strength balance and functional status of the muscles surrounding the knee joint. Huang et al [16]. also included the hamstring-to-quadriceps ratio in the assessment of lower-limb muscle strength imbalance in badminton players, supporting its relevance in badminton-specific populations. In the present study, BFR+LIFT showed a between-group advantage in the left knee flexion-to-extension ratio and a within-group improvement in the right knee flexion-to-extension ratio, indicating that the effects of BFR+LIFT were not limited to increases in peak torque, but also involved optimization of the agonist–antagonist strength relationship within the knee joint. Although previous studies differed from the present study in terms of training modality and participant population, Kara Kaya et al [29]. reported that low-load blood flow restriction training improved hamstring-to-quadriceps ratios in amateur soccer players, suggesting that BFR may have a positive influence on knee flexor–extensor strength balance. Furthermore, Zhuan et al [30]. showed that blood flow restriction during squatting progressively increased antagonist muscle activation, providing a possible neuromuscular explanation for changes in agonist–antagonist coordination under restricted blood-flow conditions. When interpreted in relation to badminton-specific movement demands, this adaptation may be particularly relevant. Lunging, braking, changing direction, and landing all require coordinated force production between the anterior and posterior muscle groups of the knee. Therefore, BFR-induced fatigue and metabolic stress may promote greater recruitment of relatively underactivated knee flexors, thereby helping to explain the observed improvement in the knee flexion-to-extension ratio. From this perspective, the increase in the knee flexion-to-extension ratio can be interpreted as a favorable adaptation in knee muscle strength balance rather than merely as an increase in the strength of a single muscle group. However, the injury-prevention implications of this finding should be interpreted cautiously. Prospective evidence has linked preseason hamstring weakness and lower hamstring-to-quadriceps strength ratios with subsequent hamstring injury in field-sport athletes [31]. However, Kellis et al [32]. noted that evidence supporting the hamstring-to-quadriceps ratio as an independent predictor of ACL or hamstring injury remains limited. Accordingly, because injury incidence was not assessed in the present study, the present findings should be interpreted as an improvement in knee muscle strength balance rather than direct evidence of reduced injury risk.

In addition to the agonist–antagonist balance within the knee joint, the reduction in knee flexor bilateral difference represents another important dimension of strength-balance adaptation after BFR+LIFT. In the present study, BFR+LIFT produced a greater reduction in knee flexor bilateral difference than both HIFT and LIFT, indicating that this training approach may have improved the side-to-side distribution of knee flexor force production rather than merely increasing absolute knee flexor strength. This adaptation is relevant to badminton-specific movement demands, as lower-limb functional asymmetry has been shown to be associated with badminton-related movement performance [33]. From a training-design perspective, the present program included several unilateral and multi-joint exercises, which required each limb to contribute to force production under controlled movement conditions. Such unilateral training components may promote inter-limb strength adaptation through neural mechanisms associated with cross-education, as unilateral strength training has been shown to induce strength gains in the contralateral limb [34]. Lv et al [18]. reported that low-load functional training combined with BFR improved lower-limb asymmetry and reduced the difference between the dominant and non-dominant limbs. They suggested that the non-dominant or weaker side may respond more markedly because of its lower training status, weaker muscular development, and poorer neuromuscular coordination, while BFR may strengthen the training stimulus of low-load functional exercise through additional internal physiological loading. Accordingly, the greater reduction in knee flexor bilateral difference after BFR+LIFT may be interpreted as a targeted inter-limb strength-balance adaptation, reflecting a more balanced distribution of knee flexor force production between limbs under the combined influence of unilateral functional exercise demands and BFR-enhanced physiological stimulation.

Regarding the ankle strength-balance outcomes, the changes in the ankle dorsiflexion-to-plantarflexion ratio require careful interpretation, because a reduction in this ratio should not be regarded as inherently favorable without considering the underlying changes in dorsiflexor and plantarflexor strength. In the present study, the pre-intervention ankle dorsiflexion-to-plantarflexion ratio was relatively high across groups. After the intervention, the BFR+LIFT and HIFT groups mainly showed increases in ankle plantarflexion relative peak torque, whereas ankle dorsiflexion strength did not change to the same extent. Therefore, the decrease in the ankle dorsiflexion-to-plantarflexion ratio more likely reflects an adjustment in the ankle flexor–extensor strength relationship following the development of plantarflexor strength, rather than a decline in dorsiflexion capacity. This change may be related to the training content of the present study, which primarily included squats, lunges, split squats, single-leg Romanian deadlifts, calf raises, and jump-based exercises, all of which place greater emphasis on the lower-limb extensor chain and ankle plantarflexion involvement. For badminton players, ankle plantarflexor strength is closely related to rapid initiation, push-off, re-acceleration, and returning to the center of the court. Thus, this result can be interpreted as an optimization of ankle strength balance following improved plantarflexor strength, which is consistent with the movement demands of badminton.

For badminton-related performance, the BFR+LIFT group showed within-group improvements in the T-test, badminton court lateral change-of-direction test, badminton court multi-directional “Mi”-shaped movement test, and 30-m sprint. In the between-group comparisons, however, the most evident advantage of BFR+LIFT was observed for 30-m sprint performance, with a significantly greater improvement than LIFT. Although the T-test, badminton court lateral change-of-direction test, and “Mi”-shaped movement test improved within the BFR+LIFT group, these changes did not reach significant between-group differences. Therefore, the advantage of BFR+LIFT in badminton-related performance should be interpreted as a broader range of improvement rather than clear superiority across all agility and footwork outcomes. The between-group advantage of BFR+LIFT in the 30-m sprint may be related to the more direct dependence of this test on lower-limb strength and rapid force production. Compared with the T-test, badminton court lateral change-of-direction test, and “Mi”-shaped movement test, the 30-m sprint has a relatively simple movement structure and is mainly influenced by hip, knee, and ankle extensor-chain strength, ankle plantarflexor push-off ability, and rapid torque development. In the present study, the BFR+LIFT group improved several lower-limb relative peak torque outcomes, knee-related muscle strength balance outcomes, and ankle plantarflexion strength, which may have provided a stronger foundation for push-off, acceleration, and repeated force production during sprinting. Previous studies have also shown that low-load BFR training can improve rapid torque development, and meta-analytic evidence indicates that BFR training can enhance lower-limb explosive power and sprint-related performance [35, 36]. Therefore, the advantage of BFR+LIFT over LIFT in 30-m sprint performance may be explained by the combined effects of functional movement stimulation, lower-limb strength improvement, and the internal physiological stimulus induced by BFR.

In contrast, the T-test, badminton court lateral change-of-direction test, and “Mi”-shaped movement test represent more complex agility and footwork tasks. These tests depend not only on lower-limb strength and rapid force production, but also on braking ability, center-of-mass transition, directional switching, footwork rhythm, body control, and sport-specific technical skill. In particular, the “Mi”-shaped movement test and badminton court lateral change-of-direction test more closely reflect the movement characteristics of badminton court play, and performance in these tasks may not improve linearly with increases in strength. Previous research on BFR

combined with functional training has also shown that this type of training tends to produce more consistent improvements in speed and explosive performance outcomes, whereas between-group advantages in complex agility performance are not always consistent [18]. Therefore, BFR+LIFT primarily improve foundational physical qualities such as lower-limb strength and explosive power, whereas the transfer of these adaptations to complex agility and badminton-specific footwork performance may still be influenced by braking ability, sport-specific footwork rhythm, and technical proficiency.

## Practical applications

From a practical perspective, the present findings suggest that BFR+LIFT may be considered a feasible low-load training strategy for improving lower-limb strength and muscle strength balance in amateur badminton players. Amateur players often have limited training time, varied strength-training backgrounds, differences in movement-control ability, and limited tolerance to high-load resistance training. Reliance solely on high-intensity functional training may increase training fatigue and the risk of compensatory movement, whereas low-intensity functional training alone may not provide a sufficient strength stimulus. In the present study, BFR+LIFT produced lower-limb strength gains comparable to those of HIFT while using only a 30% 1RM external load, and showed advantages in knee flexor bilateral difference, knee flexion-to-extension ratio, and 30-m sprint performance. Therefore, BFR+LIFT may be particularly useful for developing the lower-limb strength foundation of amateur badminton players, improving selected knee-related muscle strength balance outcomes, and supporting court-based movement tasks such as rapid initiation, push-off, change of direction, and recovery to the center of the court. Given the importance of muscle strength balance for injury-risk monitoring, movement-pattern optimization, and physical conditioning, the improvements in knee flexor bilateral difference and knee flexion-to-extension ratio observed after BFR+LIFT may also provide practical reference for lower-limb strength-balance monitoring, movement-quality optimization, and injury-risk management in amateur badminton players.

In terms of training-period application, BFR+LIFT should be considered as a supplement to HIFT or as a phase-specific alternative, rather than as a complete replacement for high-intensity functional training. For training phases focused on maximal strength development, high-load tolerance, and high-intensity neuromuscular adaptation, HIFT remains important and should not be disregarded. By contrast, the practical advantage of BFR+LIFT lies in maintaining an effective training stimulus under lower external loading conditions. Thus, during competition periods, accumulated training-load phases, recovery phases, or periods with a high volume of badminton-specific court movement training, BFR+LIFT may be used to replace part of high-load strength training to reduce mechanical load accumulation and the negative effects of fatigue on movement quality. It may also be used as a supplementary stimulus between high-intensity training days to help maintain lower-limb strength and selected muscle strength balance adaptations. In terms of exercise selection, training may continue to emphasize squats, lunges, split squats, single-leg Romanian deadlifts, calf raises, and core-stability exercises. Once a basic strength adaptation has been established, these exercises may be progressively integrated with rapid initiation, braking, change-of-direction, and footwork-combination drills to facilitate the transfer of strength adaptations to badminton-specific court movement performance.

The implementation of BFR training should also be carefully standardized. Patterson et al [11]. indicated that the effectiveness and safety of BFR training are influenced by cuff width, restriction pressure, inflation duration, training load, inter-set rest, and individual differences. Therefore, when BFR+LIFT is applied to amateur badminton players, it should be performed under appropriate pressure prescription and professional supervision, with adjustments based on training status, fatigue level, and individual tolerance. A uniform pressure should not be applied indiscriminately, and cuff inflation time should not be extended blindly. Training should also be discontinued or modified when technical execution deteriorates markedly. Overall, the practical value of BFR+LIFT lies in providing a relatively high internal training stimulus under low external load, allowing amateur badminton players to improve lower-limb strength, selected muscle strength balance outcomes, and rapid movement ability while controlling training fatigue and mechanical stress.

## Limitations and future directions

Several limitations should be acknowledged. First, the participants were amateur badminton players, and the sample size was relatively limited. Therefore, whether the present findings can be generalized to elite athletes, athletes of different sexes, or athletes from other racket sports requires further investigation. Second, the intervention period lasted 8 weeks, and the findings primarily reflect short-term training adaptations. The long-term effects of BFR+LIFT, as well as the retention of training adaptations after the intervention, remain unclear. Third, the present study mainly evaluated training effects using isokinetic strength testing and badminton-related performance assessments, without simultaneous measurements of electromyography, muscle morphology, kinematics, plantar pressure, or injury incidence. Therefore, the effects of BFR+LIFT on muscle recruitment patterns, movement-control quality,

transfer to badminton-specific movement technique, and injury risk should be further examined in future studies using more direct mechanistic measures, three-dimensional motion analysis, and long-term follow-up designs.

## Conclusion

The present study showed that 8 weeks of BFR+LIFT enabled amateur badminton players to achieve improvements in lower-limb relative peak torque that were broadly comparable to those observed after HIFT, despite using an external load of only 30% 1RM. This suggests that blood flow restriction may enhance the training stimulus of low-intensity functional training. In addition to strength gains, the adaptations in muscle strength balance induced by BFR+LIFT appeared to be selective, mainly reflected by reduced knee flexor bilateral difference and increased knee flexion-to-extension ratio, indicating that this approach may help optimize knee-related strength distribution and the agonist–antagonist strength relationship. In terms of performance, the most evident improvement after BFR+LIFT was observed in 30-m sprint performance, while within-group improvements were also found in the T-test, badminton court lateral change-of-direction test, and badminton court multi-directional “Mi”-shaped movement test. Overall, adding blood flow restriction to low-intensity functional training may allow amateur badminton players to obtain meaningful lower-limb strength adaptations under relatively low external loads, accompanied by improvements in selected knee-related muscle strength balance and sprint-related performance. Therefore, BFR+LIFT may provide a practically valuable low-load training strategy for badminton-specific conditioning in amateur players.

## Declarations

## Competing interests

The authors declare no competing interests.

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## Author Contribution

W.H. and D.T. conceived and designed the study. W.H. recruited participants, implemented the intervention, collected data, performed the statistical analyses, prepared the figures and tables, and drafted the manuscript. D.T. supervised the study, contributed to the study design and interpretation of the results, and critically revised the manuscript for important intellectual content. Both authors reviewed and approved the final manuscript.

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## Data Availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

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## Figures

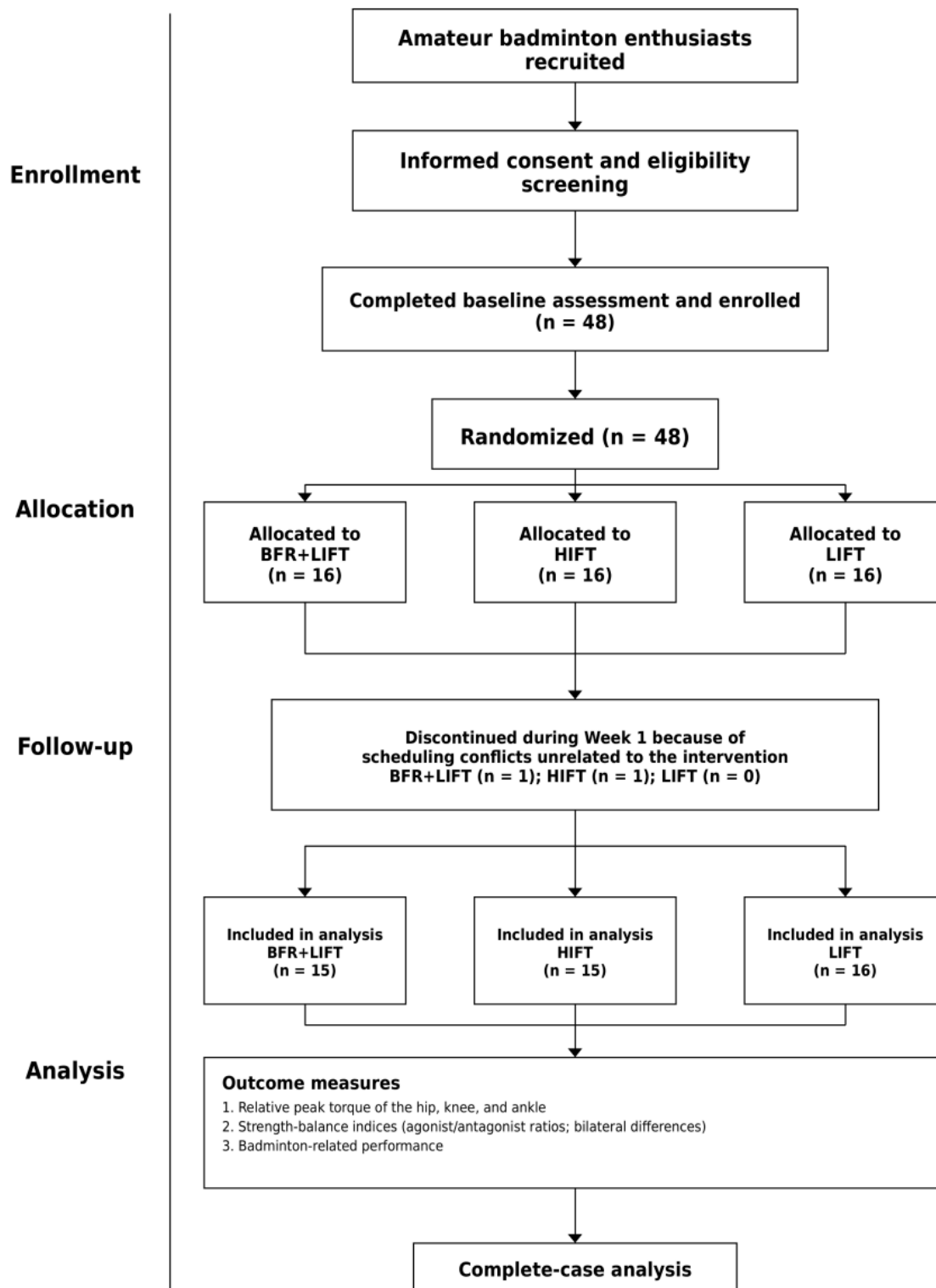


**Figure 1**

CONSORT flowchart of participant recruitment, randomization, attrition, and complete-case analysis. BFR+LIFT = blood flow restriction combined with low-intensity functional training; HIFT = high-intensity functional training; LIFT = low-intensity functional training.

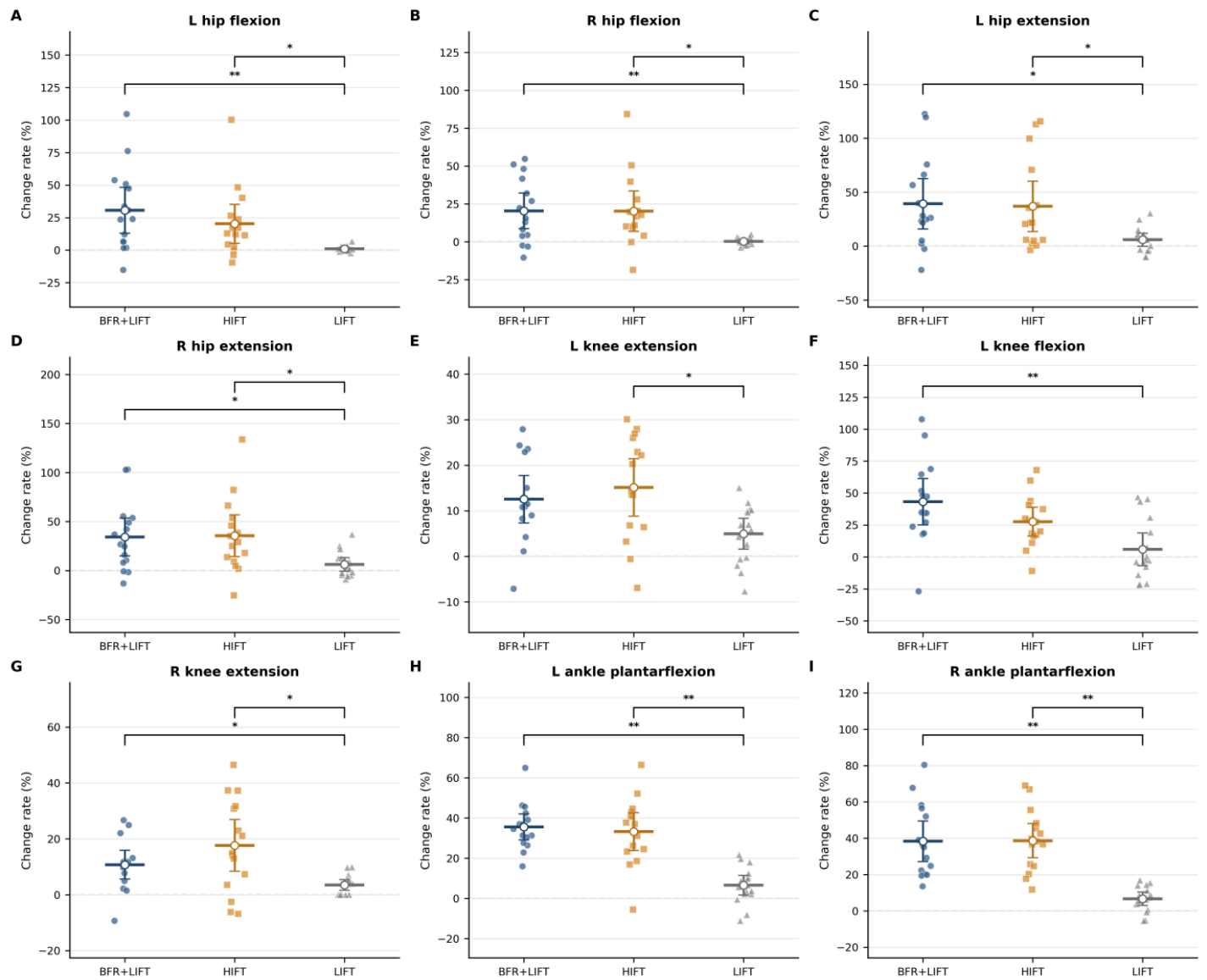


**Figure 2**

Changes in lower-limb isokinetic strength outcomes after the intervention. Individual dots represent participant-level change rates. Horizontal bars and error bars represent group means and 95% confidence intervals, respectively. Brackets indicate significant post hoc pairwise comparisons. \*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ . Exact  $p$  values are reported in the corresponding results tables.

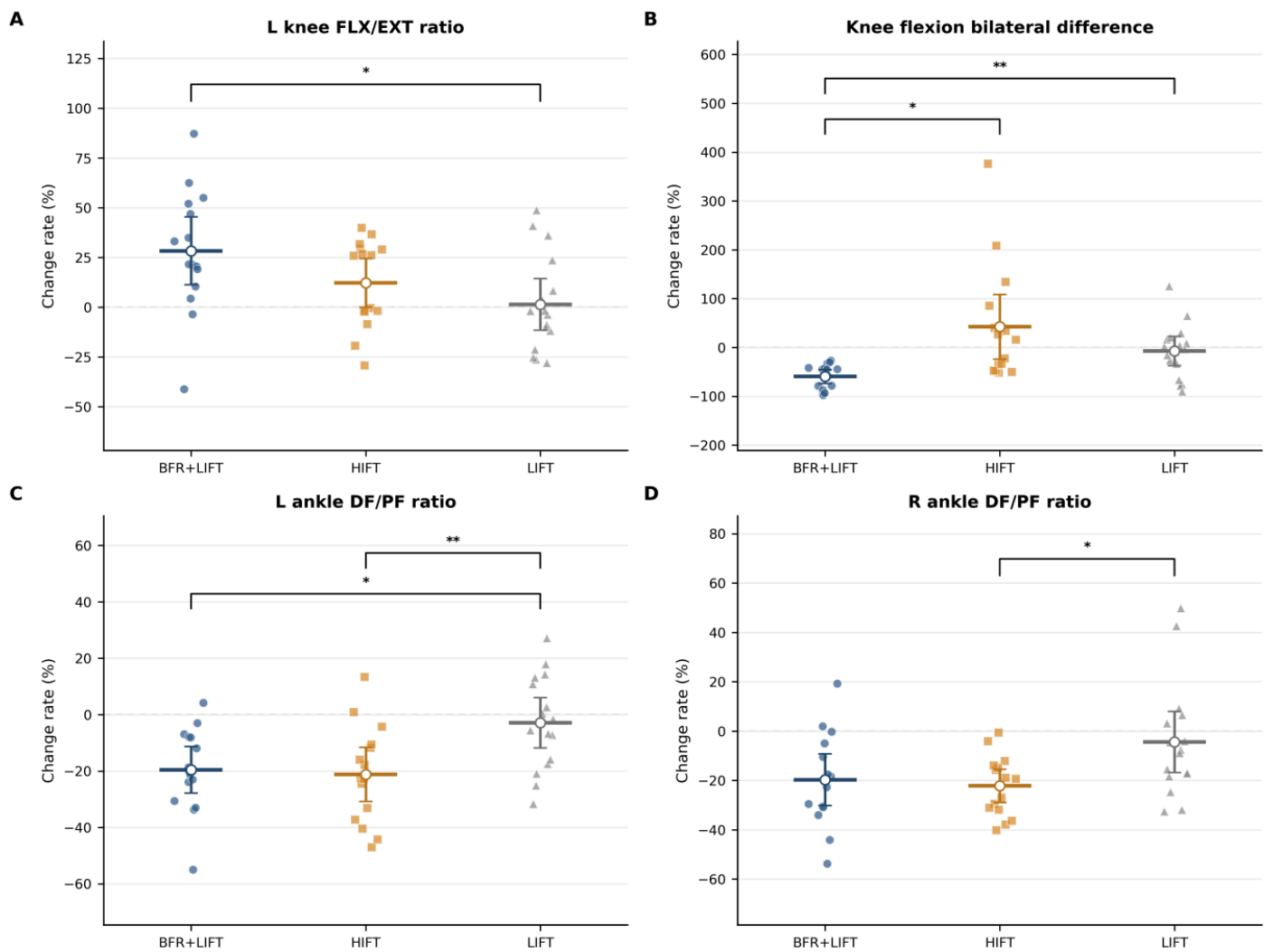


**Figure 3**

Changes in muscle strength-balance outcomes after the intervention. Individual dots represent participant-level change rates. Horizontal bars and error bars represent group means and 95% confidence intervals, respectively. Brackets indicate significant post hoc pairwise comparisons. \*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ . Exact  $p$  values are reported in the corresponding results tables.

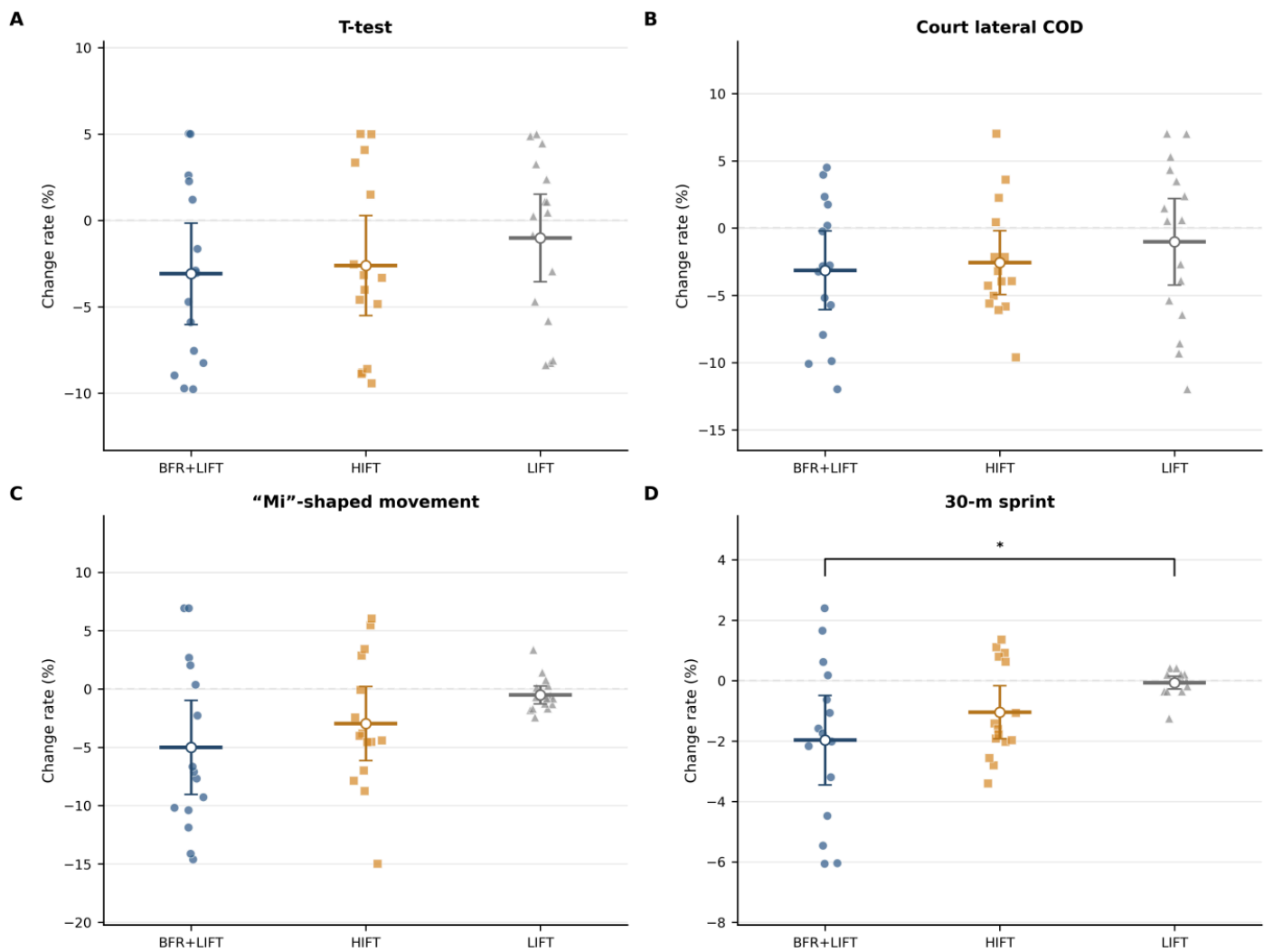


**Figure 4**

Changes in badminton-related performance outcomes after the intervention. Individual dots represent participant-level change rates. Horizontal bars and error bars represent group means and 95% confidence intervals, respectively. Brackets indicate significant post hoc pairwise comparisons. \*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ . Exact  $p$  values are reported in the corresponding results tables. For timed performance tests, negative change rates indicate improved performance.