

Effects of Three Fixed Cuff Pressures During Low-Load Blood Flow Restriction Training Versus High-Load Resistance Training on Upper-Limb Strength and Sport-Specific Arm-Swing Performance in Male Collegiate Volleyball Players

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Abstract

Objective

To compare low-load blood flow restriction resistance training (BFRT) performed at three fixed cuff pressures with traditional high-load resistance training (HLRT) for improving upper-limb performance in male collegiate volleyball players.

Methods

Thirty-two players were randomized to BFRT-100, BFRT-140, BFRT-180, or HLRT ($n = 8/\text{group}$). BFRT groups trained at 30% 1RM with cuff pressures of 100, 140, or 180 mmHg, whereas HLRT trained at 70% 1RM. Training was performed twice weekly for 8 weeks. Peak wrist arm-swing velocity, dominant-arm single-arm medicine ball throw, bench press 1RM, and bilateral upper-arm circumference were assessed before and after training. Data were analyzed using two-way repeated-measures ANOVA.

Results

Significant time effects and group $\times$ time interactions were found for all outcomes (all $p < 0.05$). BFRT-140 improved medicine ball throw more than BFRT-100 ($p = 0.04$), while HLRT increased bench press 1RM more than BFRT-100 ($p = 0.01$). BFRT-180 produced greater increases in left upper-arm circumference than BFRT-100 and HLRT, whereas BFRT-140 and BFRT-180 produced greater increases in right upper-arm circumference than BFRT-100 (all $p < 0.05$). No adjusted between-group difference was observed for arm-swing velocity.

Conclusion

Both low-load BFRT and HLRT improved upper-limb performance and arm circumference, but their advantages were outcome-specific. Moderate-to-high fixed-pressure BFRT may benefit throwing performance and arm circumference, whereas HLRT may be more effective for maximal strength. No fixed pressure was clearly superior for arm-swing velocity.

Trial Registration

[http://www.chictr.org.cn/\(ChiCTR2500109281\)](http://www.chictr.org.cn/(ChiCTR2500109281)), registered on 16/9/2025.

1. Introduction

The spike and serve are among the most decisive offensive skills in volleyball. Their effectiveness depends not only on jump height, contact timing, and movement accuracy, but also on distal upper-limb velocity and the efficiency of force transmission. The volleyball arm swing is a typical overhead whipping action in which mechanical energy generated by proximal segments is transferred sequentially to distal segments through trunk rotation, shoulder internal rotation, elbow extension, and rapid wrist motion. Three-dimensional kinematic studies have demonstrated a clear proximal-to-distal sequencing pattern during the volleyball spike, with the angular velocities and coordination of the shoulder, elbow, and wrist jointly influencing distal-segment velocity during ball contact^[1, 2]. Successful spikes are generally characterized by more effective coordination among the lower limbs, trunk, and upper limbs, together with greater wrist velocity^[3]. Therefore, although peak wrist velocity measured during a standardized arm-swing task cannot be considered equivalent to ball-release velocity or scoring effectiveness, it may serve as a relevant kinematic indicator of distal velocity output within the upper-limb kinetic chain and of sport-specific arm-swing performance.

Upper-limb strength and power constitute important physical foundations for generating a high-velocity arm swing and rapid ball striking. Previous research in high-level male volleyball players has shown that force- and velocity-related characteristics obtained during the ballistic bench press throw, particularly theoretical maximal force, are significantly associated with spike and serve ball velocity. These mechanical variables explained approximately 20%–36% of the between-athlete variance in ball velocity, indicating that upper-limb strength is one of several important determinants of volleyball-specific striking performance^[4]. Nevertheless, increases in maximal strength do not necessarily transfer directly to fast, unilateral, and multisegmental sport actions such as the volleyball spike. Facilitating the transfer of general strength adaptations to sport-specific arm-swing velocity is therefore an important issue in volleyball strength and conditioning. Traditional moderate- to high-load resistance training is effective for developing maximal strength; however, when technical training, competition, and recovery demands are high, large external loads may increase athletes' mechanical burden. Accordingly, training methods that maintain or improve upper-limb strength and sport-specific velocity while reducing external training load may have substantial practical value.

Blood flow restriction resistance training combines low-load resistance exercise with external cuff pressure applied to the proximal portion of a limb. Low-load BFRT is commonly performed at approximately 20%–40% 1RM and can generate substantial local metabolic stress despite the relatively low external mechanical load. Local hypoxia, metabolite accumulation, cell swelling, altered motor-unit recruitment, and enhanced muscle-protein-synthesis signaling have all been proposed as contributors to strength and muscular adaptations^[5, 6]. Systematic reviews and meta-analyses indicate that BFRT generally produces greater strength and morphological adaptations than non-occluded low-load training performed at a similar intensity. Compared with traditional high-load training, low-load BFRT may produce broadly comparable hypertrophic adaptations, although high-load training generally retains an advantage for maximal strength development^[5, 7]. The potential value of BFRT should therefore not be

evaluated solely through muscle circumference or general strength; whether these adaptations transfer to sport-specific performance should also be examined.

Long-term evidence regarding upper-limb BFRT remains less extensive than that for lower-limb applications. An early study reported that low-load bench press training at 30% 1RM with blood flow restriction increased bench press 1RM and induced morphological adaptations in both the restricted triceps brachii and the non-restricted pectoralis major^[8]. Subsequent systematic reviews suggested that upper-limb BFRT may improve strength and muscle morphology in muscles located both distal and proximal to the cuff, although the available evidence is heterogeneous with respect to participant characteristics, cuff devices, exercises, applied pressures, and intervention duration^[9, 10]. Meta-analyses in athletes also suggest that BFRT can improve strength, power, speed, and selected sport-performance outcomes; however, most studies have focused on lower-limb physical capacities or general strength measures, and long-term evidence for high-velocity, sport-specific upper-limb actions remains limited^[11]. A recent randomized trial in elite boxers reported improvements in upper-body strength and punching force after low-load BFRT, suggesting potential transfer to sport-specific performance. Nevertheless, that study did not systematically compare multiple pressure levels, and the movement pattern and sport demands differ substantially from the volleyball arm swing^[12].

In addition to exercise load, cuff pressure is a key prescription variable that determines the characteristics of the BFRT stimulus. In theory, higher cuff pressures may increase local blood flow restriction and metabolic stress, but greater pressure does not necessarily result in greater long-term adaptation. Counts et al.^[13] found that higher relative restriction pressures altered acute muscle activation and perceptual responses, whereas long-term strength and muscle adaptations did not display a simple linear difference across pressures. Lixandrão et al.^[14] further suggested that pressure effects may depend on exercise load, whether training is performed to fatigue, and the outcome assessed. BFRT may therefore involve a minimum effective stimulus, an adaptive plateau, or a nonlinear pressure-response relationship rather than a simple higher-is-better pattern. A 2026 randomized controlled trial in youth soccer players compared different individualized arterial occlusion pressure levels for body-composition and performance outcomes; however, the intervention focused primarily on the lower limbs and does not resolve the relationship between upper-limb pressure prescription and volleyball arm-swing performance^[15].

Standardization of pressure prescription is another methodological issue that must be considered when interpreting previous findings. The same absolute pressure does not produce the same degree of blood flow restriction in every participant because actual occlusion is also influenced by cuff width and material, upper-arm circumference, systolic blood pressure, limb position, and device characteristics^[5, 16]. Although individualized arterial occlusion pressure can improve the comparability of the pressure stimulus among participants, comparing multiple fixed absolute pressures while holding the device, cuff width, placement, and exercise load constant still addresses an important practical question: whether

progressively increasing the device pressure setting in a real-world training environment alters long-term adaptations and sport-performance benefits from low-load BFRT.

Collectively, previous studies provide substantial evidence that low-load BFRT can improve muscular strength and morphology, but at least three questions remain unresolved. First, most studies have used a single restriction pressure, making it difficult to determine whether greater pressure provides additional benefits. Second, upper-limb studies have primarily assessed general outcomes such as muscle thickness, isometric strength, or 1RM, with limited attention to rapid unilateral actions and sport-specific kinematic performance. Third, few studies in athletes have compared multiple fixed pressures under the same low-load condition while including traditional high-load resistance training as a practical reference. Accordingly, the value of the present study lies not in re-establishing whether BFRT can improve general strength, but in determining whether fixed cuff pressure influences the transfer of upper-limb strength adaptations to unilateral power and volleyball-specific arm-swing velocity.

To address these gaps, the present study compared three fixed-pressure low-load BFRT protocols (100, 140, and 180 mmHg combined with 30% 1RM) with traditional HLRT at 70% 1RM in male collegiate volleyball players over 8 weeks, with two sessions per week. Peak wrist velocity during the arm swing was designated as the primary outcome to evaluate distal velocity output during a sport-specific arm-swing task. Dominant-arm single-arm medicine ball throw distance and bench press 1RM were selected as key secondary outcomes reflecting unilateral upper-limb power and general maximal strength, respectively, whereas upper-arm circumference was treated as an exploratory morphological outcome. The study aimed to determine whether different fixed cuff pressures produced distinct strength and sport-performance adaptations under an otherwise identical low-load protocol, and to compare low-load BFRT with traditional HLRT for improving arm-swing velocity and upper-limb performance.

We hypothesized that peak wrist velocity, dominant-arm single-arm medicine ball throw distance, and bench press 1RM would improve to different extents across all training groups after 8 weeks. Pressure-related differences were expected among the three BFRT groups, although not necessarily as a simple linear increase. Compared with 100 mmHg, fixed pressures of 140 and 180 mmHg were expected to provide a greater training stimulus, whereas the highest pressure might not confer additional sport-performance benefits. We further hypothesized that low-load BFRT would produce practically meaningful improvements in upper-limb strength and arm-swing performance while substantially reducing the external training load.

2. Methods

2.1. Study Design

This randomized parallel-group controlled trial was conducted over 10 weeks. Participant screening, test familiarization, and baseline assessments were completed in week 1; the 8-week training intervention was implemented during weeks 2–9; and post-intervention assessments were conducted in week 10.

Post-testing was performed at least 48 h after the final training session. Pre- and post-intervention assessments were conducted at the same venue and at similar times of day, using the same equipment and standardized procedures administered by the same assessors. Participants were instructed to avoid strenuous exercise and alcohol for 24 h before testing and to maintain their usual diet, sleep habits, and volleyball-specific training. The study was designed and reported in accordance with the CONSORT 2025 statement^[17].

After baseline testing, an investigator who was not involved in recruitment, training supervision, or outcome assessment generated a computer-based randomization sequence and allocated participants in equal proportions to the 100-mmHg BFRT group (BFRT-100), 140-mmHg BFRT group (BFRT-140), 180-mmHg BFRT group (BFRT-180), or traditional HLRT group ($n = 8$ per group). Allocation assignments were placed in sequentially numbered, opaque, sealed envelopes, which were opened in order after completion of baseline testing. Because the differences in cuff pressure and training load were apparent, participants and training supervisors could not be blinded. Outcome assessors and the statistical analyst remained unaware of group allocation until study completion.

All three BFRT groups trained at 30% 1RM and differed only in fixed cuff pressure, whereas the HLRT group trained without cuff application at 70% 1RM. Peak wrist velocity during the arm swing was the primary outcome; dominant-arm single-arm medicine ball throw distance and bench press 1RM were key secondary outcomes; and upper-arm circumference was an exploratory outcome (Fig. 2).

2.2. Participants

An a priori sample-size calculation was performed using G*Power. The test was specified as the group $\times$ time interaction in a repeated-measures analysis of variance, with an effect size of $f = 0.50$, $\alpha = 0.05$, statistical power of 0.85, four groups, two measurements, an assumed correlation of 0.50 between repeated measures, and a nonsphericity correction of 1.00. The analysis indicated that at least 32 participants were required^[18].

Eligible participants were male university students with systematic volleyball-specific training experience who could complete all training and testing procedures without pain and had not previously undertaken systematic BFRT. Exclusion criteria included contraindications to BFRT such as cardiovascular disease, hypertension, peripheral vascular disease, thrombosis, or coagulation disorders; shoulder, elbow, wrist, or spinal injuries that could affect training or testing; recent relevant surgery; use of medication that could influence vascular responses, coagulation, or neuromuscular performance; and concurrent participation in other systematic upper-limb resistance-training programs during the study.

Thirty-two male volleyball-specialized students from Guangzhou Sport University were ultimately recruited (Table 1). Based on the participant classification framework proposed by McKay et al., and considering years of sport-specific training, training volume, competition level, and competitive achievement, participants were classified as Tier 3^[19]. All participants provided written informed consent after receiving a full explanation of the study purpose, procedures, potential risks, and benefits. The

study was conducted in accordance with the Declaration of Helsinki, approved by the Ethics Committee of Guangzhou Sport University, and registered with the Chinese Clinical Trial Registry (ChiCTR2500109281).

Table 1
Participant characteristics.

Height (cm)	BFRT-100	BFRT-140	BFRT-180	HLRT	p
	183.25 ± 6.69	184.38 ± 2.39	185.25 ± 5.84	185.38 ± 3.89	0.82
Body mass (kg)	73.56 ± 4.54	77.75 ± 10.42	79.38 ± 6.32	81.38 ± 10.98	0.32
Age (years)	20.36 ± 0.74	20.25 ± 0.71	20.25 ± 1.49	20.63 ± 0.52	0.84
Training experience (years)	6.00 ± 1.31	6.75 ± 1.49	6.50 ± 0.93	5.63 ± 1.60	0.36

2.3. Blood Flow Restriction Device and Pressure Settings

All BFRT groups used a KAATSU MASTER pressure-training system (KAATSU, Japan) fitted with 6-cm-wide upper-limb cuffs. During training, cuffs were positioned proximally on both upper arms and set to 100, 140, or 180 mmHg according to group allocation. The same investigator applied the cuffs and checked the pressure at every session.

Pressures of 100 and 180 mmHg were selected to represent the lower and upper ends of the fixed-pressure range used in previous upper-limb BFRT studies, with 140 mmHg chosen as the equally spaced midpoint, thereby creating three pressure levels separated by 40 mmHg^[20–23]. Before each exercise, the cuffs were inflated to the target pressure and remained inflated throughout all four sets and intersets rest intervals for that exercise. Pressure was released after completion of the exercise before proceeding to the next exercise. Because the actual degree of blood flow restriction produced by an absolute pressure is influenced by factors such as cuff width, upper-arm circumference, and blood pressure, the three conditions are described as fixed cuff pressures rather than individualized percentages of arterial occlusion pressure^[20, 24].

2.4. Training Intervention

The intervention lasted 8 weeks and consisted of two sessions per week (16 sessions in total), with at least 48 h between consecutive sessions. Each session began with a standardized dynamic upper-limb warm-up. The training exercises were performed in the following order: bench press and lying overhead triceps extension. Exercises, exercise order, and training frequency were identical across groups.

All BFRT groups trained at 30% 1RM. For each exercise, participants completed four sets of 30, 15, 15, and 15 repetitions (75 repetitions in total). The HLRT group trained at 70% 1RM and completed four sets of eight repetitions for each exercise. Intersets rest was 30–60 s in all groups, and the same rest duration

was maintained for each participant across sessions. Repetition tempo was approximately 1 s for the concentric phase and 2 s for the eccentric phase, with no deliberate pause during the transition; cadence was standardized using verbal commands from the investigator. The intensity, set-repetition structure, rest intervals, and frequency of low-load BFRT were based on methodological recommendations^[20, 21], whereas the HLRT load and repetition scheme followed conventional resistance-training guidelines^[25].

During the bench press, participants lay supine with the head, shoulders, and buttocks in contact with the bench, lowered the barbell under control to the chest, and pressed it until both elbows were fully extended^[26, 27]. During the lying overhead triceps extension, participants lay supine on a bench with the upper arms held relatively stationary, lowered the load behind the head through elbow flexion, and returned to the starting position by extending the elbows. All sessions were completed under investigator supervision with appropriate spotting.

The actual load, completed sets, repetitions, attendance, and adverse events were recorded at every session. Throughout the study, participants maintained their usual volleyball-specific training and daily routines and were not permitted to undertake additional systematic upper-limb resistance training.

2.5. Outcomes and Testing Procedures

2.5.1. Peak Wrist Velocity During the Arm Swing

Peak wrist velocity during the arm swing was recorded using a PUSH Band 2.0 wearable inertial sensor (PUSH Inc., Toronto, Canada)^[28, 29]. The device was secured to the wrist of the participant's dominant spiking arm. Participants adopted a staggered stance and performed a stationary volleyball spike against a ball fixed on an auxiliary spike stand, without an approach or jump. The stand was adjusted to each participant's customary contact height and maintained at the same height during pre- and post-testing. Participants completed three maximal valid trials separated by 30 s of rest. Peak velocity was recorded automatically in $\text{m}\cdot\text{s}^{-1}$, and the best of the three trials was used for analysis. The same device, placement location, and testing procedure were used at both time points.

2.5.2. Dominant-Arm Single-Arm Medicine Ball Throw

Dominant-side upper-limb power was assessed using a 1-kg medicine ball^[30]. Participants adopted a staggered stance and held the ball behind the shoulder with the dominant hand. They performed a maximal single-arm overarm throw without an approach and without crossing the throwing line. The perpendicular distance from the throwing line to the ball's first point of contact was measured to the nearest 0.01 m. Each participant completed three valid trials separated by 60 s, and the best performance was used for analysis. The same medicine ball, stance, and measurement procedure were used before and after the intervention.

2.5.3. Bench Press 1RM

Upper-limb maximal dynamic strength was assessed using a standardized bench press 1RM test^[31]. After a standardized warm-up, participants completed 8–10 repetitions at approximately 50% of the estimated 1RM and 3–5 repetitions at approximately 70%, followed by progressive loading. After each successful attempt, the load was increased by 2.5–5.0 kg, with 3–5 min of rest between maximal attempts. Throughout testing, the head, shoulders, and buttocks remained in contact with the bench, and the barbell was lowered to the chest and pressed until both elbows were fully extended. The heaviest load completed once with the standardized technique was recorded as the bench press 1RM. Testing was completed within three to five maximal attempts whenever possible.

2.5.4. Upper-Arm Circumference

Dominant- and non-dominant-side upper-arm circumference was measured using a non-stretchable tape. Participants stood naturally with the arms relaxed at their sides. The midpoint between the acromion and olecranon was used as the measurement site. The tape was positioned perpendicular to the longitudinal axis of the upper arm without compressing the skin, and measurements were recorded to the nearest 0.1 cm. Three consecutive measurements were averaged. The same assessor performed all pre- and post-intervention measurements.

2.6. Statistical Analysis

Statistical analyses were performed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables are presented as mean $\pm$ standard deviation. Normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene tests, respectively. A 4-group $\times$ 2-time-point two-way repeated-measures analysis of variance was used to examine the main effects of group and time and the group $\times$ time interaction. When the interaction was statistically significant, simple-effects analyses and between-group pairwise comparisons were performed with Bonferroni adjustment for multiple comparisons. Results are reported as F values, p values, 95% confidence intervals (CIs), and partial eta squared (η^2)^[32]. Statistical significance was set at $p < 0.05$, and the group $\times$ time interaction served as the primary basis for inference.

3. Results

All 32 participants completed the 8-week intervention and the pre- and post-intervention assessments according to the protocol, with no withdrawals or missing outcome data. No adverse event requiring training cessation, medical treatment, or withdrawal occurred during the intervention. Significant main effects of time and significant group $\times$ time interactions were observed for all five outcomes.

Based on descriptive mean changes (Table 2), BFRT-140 showed the largest improvements in peak wrist velocity during the arm swing and dominant-arm single-arm medicine ball throw distance; HLRT showed the largest improvement in bench press 1RM; BFRT-180 showed the largest increase in left upper-arm circumference; and BFRT-140 and BFRT-180 showed similar increases in right upper-arm circumference. After Bonferroni adjustment, no between-group difference in change reached statistical significance for

peak wrist velocity. The improvement in medicine ball throw distance was greater in BFRT-140 than in BFRT-100; the improvement in bench press 1RM was greater in HLRT than in BFRT-100; the increase in left upper-arm circumference was greater in BFRT-180 than in BFRT-100 and HLRT; and the increases in right upper-arm circumference were greater in BFRT-140 and BFRT-180 than in BFRT-100 (Fig. 4).

Table 2
Descriptive statistics for pre- and post-intervention outcomes by group.

Outcome	Time	BFRT-100 (n = 8)	BFRT-140 (n = 8)	BFRT-180 (n = 8)	HLRT (n = 8)
Peak wrist velocity during arm swing (m·s ⁻¹)	Pre	8.82 ± 1.64	9.54 ± 1.54	10.05 ± 1.77	9.92 ± 1.07
	Post	9.45 ± 1.46	10.71 ± 1.48	11.09 ± 1.79	10.50 ± 1.39
Dominant-arm single-arm medicine ball throw (m)	Pre	20.31 ± 1.39	21.39 ± 1.37	21.21 ± 1.90	21.12 ± 1.10
	Post	21.05 ± 1.62	22.69 ± 1.72	22.29 ± 1.99	22.01 ± 1.11
Bench press 1RM (kg)	Pre	62.88 ± 9.12	64.75 ± 18.18	68.13 ± 11.93	74.50 ± 14.47
	Post	67.63 ± 8.67	70.50 ± 17.68	75.38 ± 12.28	83.00 ± 14.70
Left upper-arm circumference (cm)	Pre	29.53 ± 1.02	31.45 ± 2.83	31.65 ± 1.47	31.90 ± 2.76
	Post	29.95 ± 0.80	32.26 ± 2.80	32.64 ± 1.59	32.34 ± 2.80
Right upper-arm circumference (cm)	Pre	31.90 ± 2.76	31.89 ± 3.09	32.91 ± 1.19	32.36 ± 3.23
	Post	32.19 ± 2.74	32.69 ± 2.86	33.73 ± 1.23	32.90 ± 3.22

3.1. Peak Wrist Velocity During the Arm Swing

Two-way repeated-measures analysis of variance revealed a significant main effect of time for peak wrist velocity during the arm swing, $F(1, 28) = 134.24$, $p < 0.001$, $\eta^2 = 0.83$, indicating an overall increase after training. The group $\times$ time interaction was also significant, $F(3, 28) = 3.86$, $p = 0.020$, $\eta^2 = 0.29$, indicating that the magnitude of improvement differed among training groups.

Simple-effects analyses showed that peak wrist velocity increased by 0.64 m·s⁻¹ in BFRT-100 (95% CI: 0.33–0.94 m·s⁻¹, $p < 0.001$, Cohen's $d = 0.41$), by 1.18 m·s⁻¹ in BFRT-140 (95% CI: 0.87–1.48 m·s⁻¹, $p < 0.001$, $d = 0.78$), by 1.04 m·s⁻¹ in BFRT-180 (95% CI: 0.74–1.35 m·s⁻¹, $p < 0.001$, $d = 0.59$), and by 0.59

m·s⁻¹ in HLRT (95% CI: 0.28–0.89 m·s⁻¹, $p = 0.002$, $d = 0.47$). Descriptively, BFRT-140 showed the largest improvement, followed by BFRT-180; however, Bonferroni-adjusted pairwise comparisons indicated that no between-group difference in change was statistically significant (all $p > 0.05$).

3.2. Dominant-Arm Single-Arm Medicine Ball Throw

A significant main effect of time was observed for dominant-arm single-arm medicine ball throw distance, $F(1, 28) = 216.91$, $p < 0.001$, $\eta^2 = 0.89$. The group $\times$ time interaction was also significant, $F(3, 28) = 3.20$, $p = 0.039$, $\eta^2 = 0.26$, indicating that the magnitude of improvement differed among training protocols.

Simple-effects analyses showed increases of 0.74 m in BFRT-100 (95% CI: 0.46–1.02 m, $p < 0.001$, Cohen's $d = 0.49$), 1.31 m in BFRT-140 (95% CI: 1.03–1.59 m, $p < 0.001$, $d = 0.84$), 1.07 m in BFRT-180 (95% CI: 0.79–1.35 m, $p < 0.001$, $d = 0.55$), and 0.89 m in HLRT (95% CI: 0.61–1.17 m, $p < 0.001$, $d = 0.81$).

Bonferroni-adjusted post hoc comparisons showed that the improvement in BFRT-140 was greater than that in BFRT-100 (mean difference in change: 0.56 m, 95% CI: 0.02–1.11 m, $p = 0.040$). No other pairwise between-group comparison reached statistical significance (all $p > 0.05$).

3.3. Bench Press 1RM

Bench press 1RM showed a significant main effect of time, $F(1, 28) = 278.61$, $p < 0.001$, $\eta^2 = 0.91$, indicating that the 8-week interventions improved maximal dynamic upper-limb strength. The group $\times$ time interaction was also significant, $F(3, 28) = 4.41$, $p = 0.012$, $\eta^2 = 0.32$, indicating differences in the magnitude of improvement among groups.

Simple-effects analyses showed increases of 4.75 kg in BFRT-100 (95% CI: 3.14–6.36 kg, $p < 0.001$, Cohen's $d = 0.53$), 5.75 kg in BFRT-140 (95% CI: 4.14–7.36 kg, $p < 0.001$, $d = 0.32$), 7.25 kg in BFRT-180 (95% CI: 5.64–8.86 kg, $p < 0.001$, $d = 0.60$), and 8.50 kg in HLRT (95% CI: 6.89–10.11 kg, $p < 0.001$, $d = 0.58$).

Bonferroni-adjusted post hoc comparisons showed that the improvement in HLRT was greater than that in BFRT-100 (mean difference in change: 3.75 kg, 95% CI: 0.59–6.91 kg, $p = 0.013$). No other pairwise between-group comparison reached statistical significance (all $p > 0.05$).

3.4. Left Upper-Arm Circumference

Left upper-arm circumference showed a significant main effect of time, $F(1, 28) = 107.40$, $p < 0.001$, $\eta^2 = 0.79$. The group $\times$ time interaction was also significant, $F(3, 28) = 4.78$, $p = 0.008$, $\eta^2 = 0.34$, indicating that the magnitude of change differed among training groups.

Simple-effects analyses showed increases of 0.42 cm in BFRT-100 (95% CI: 0.16–0.69 cm, $p = 0.011$, Cohen's $d = 0.46$), 0.81 cm in BFRT-140 (95% CI: 0.55–1.08 cm, $p < 0.001$, $d = 0.29$), 0.99 cm in BFRT-180 (95% CI: 0.72–1.25 cm, $p < 0.001$, $d = 0.64$), and 0.44 cm in HLRT (95% CI: 0.17–0.70 cm, $p = 0.008$, $d = 0.16$).

Bonferroni-adjusted post hoc comparisons showed that the increase in BFRT-180 was greater than that in BFRT-100 (mean difference in change: 0.56 cm, 95% CI: 0.05–1.08 cm, $p = 0.026$) and HLRT (mean difference in change: 0.55 cm, 95% CI: 0.03–1.06 cm, $p = 0.032$). No other pairwise between-group comparison reached statistical significance (all $p > 0.05$).

3.5. Right Upper-Arm Circumference

Right upper-arm circumference showed a significant main effect of time, $F(1, 28) = 95.57$, $p < 0.001$, $\eta^2 = 0.77$. The group $\times$ time interaction was also significant, $F(3, 28) = 3.95$, $p = 0.018$, $\eta^2 = 0.30$, indicating that the magnitude of change differed among training groups.

Simple-effects analyses showed an increase of 0.29 cm in BFRT-100 (95% CI: 0.03–0.55 cm, unadjusted $p = 0.027$; Bonferroni-adjusted $p = 0.110$, Cohen's $d = 0.11$), which did not remain statistically significant after adjustment. Increases were 0.81 cm in BFRT-140 (95% CI: 0.55–1.06 cm, $p < 0.001$, $d = 0.27$), 0.81 cm in BFRT-180 (95% CI: 0.56–1.07 cm, $p < 0.001$, $d = 0.67$), and 0.54 cm in HLRT (95% CI: 0.28–0.80 cm, $p < 0.001$, $d = 0.17$).

Bonferroni-adjusted post hoc comparisons showed that the increase in BFRT-140 was greater than that in BFRT-100 (mean difference in change: 0.51 cm, 95% CI: 0.01–1.02 cm, $p = 0.043$), and the increase in BFRT-180 was also greater than that in BFRT-100 (mean difference in change: 0.52 cm, 95% CI: 0.02–1.02 cm, $p = 0.039$). No other pairwise between-group comparison reached statistical significance (all $p > 0.05$).

4. Discussion

4.1. Main Findings

This study compared three fixed-pressure low-load BFRT protocols with traditional HLRT for their effects on upper-limb strength, power, arm-swing velocity, and upper-arm circumference in male collegiate volleyball players. After 8 weeks, significant time effects were observed for peak wrist velocity during the arm swing, dominant-arm single-arm medicine ball throw distance, bench press 1RM, and bilateral upper-arm circumference, indicating overall improvements in upper-limb performance and morphological outcomes across the training protocols. Significant group $\times$ time interactions were also observed for all five outcomes, demonstrating that the magnitude of adaptation varied according to the training load and fixed cuff-pressure protocol.

Further analyses indicated that BFRT-140 showed the largest descriptive improvements in peak wrist velocity and medicine ball throw distance, with the improvement in throw distance being significantly greater than that in BFRT-100. HLRT showed the largest improvement in bench press 1RM and was significantly superior to BFRT-100. The increase in left upper-arm circumference was greater in BFRT-180 than in BFRT-100 and HLRT, whereas increases in right upper-arm circumference were greater in BFRT-140 and BFRT-180 than in BFRT-100. These findings suggest that different outcomes may exhibit

different sensitivities to cuff pressure. Higher fixed pressures may be more favorable for arm-circumference changes and selected strength adaptations, whereas rapid sport-specific arm-swing performance did not follow a simple linear pattern in which greater pressure produced greater benefit.

4.2. Effects of the Training Protocols on Peak Wrist Velocity During the Arm Swing

Peak wrist velocity increased from pre- to post-intervention in all four groups, and the group $\times$ time interaction was statistically significant. Descriptively, BFRT-140 showed the largest improvement, followed by BFRT-180. However, no pairwise between-group difference in change remained significant after Bonferroni adjustment. The findings therefore indicate that the pattern of arm-swing velocity adaptation may differ among protocols, but they do not support the conclusion that training at 140 mmHg was significantly superior to the other fixed pressures or to HLRT.

The volleyball spike is a typical proximal-to-distal kinetic-chain action. Arm-swing velocity is not determined by maximal strength in a single muscle group but by the coordinated contribution of trunk rotation, shoulder internal rotation, elbow extension, and distal-segment acceleration^[33]. Wagner et al. identified clear proximal-to-distal kinematic sequencing in the volleyball spike, handball throw, and tennis serve^[34], and Wang et al. further reported that trunk involvement can substantially increase arm-swing velocity and power in volleyball players^[35]. Force- and velocity-related characteristics during the ballistic bench press throw are also associated with spike and serve ball velocity in high-level male volleyball players, indicating that rapid upper-limb force production is an important physical foundation for sport-specific striking velocity^[33].

Low-load BFRT may promote strength and velocity adaptations under relatively low mechanical loads by increasing local metabolic stress, facilitating high-threshold motor-unit recruitment, and enhancing neuromuscular output^[36, 37]. A meta-analysis in athletes also reported small-to-large positive effects of BFRT on strength, power, and speed, with intervention duration, frequency, load, and pressure acting as potential moderators^[38]. The comparatively large mean increases in arm-swing velocity in BFRT-140 and BFRT-180 may therefore be related to the metabolic stimulus created by high-repetition low-load training and the use of rapid concentric actions.

Nevertheless, the lack of significant pairwise between-group differences means that the present evidence is insufficient to identify an optimal fixed pressure for arm-swing velocity. Moreover, arm-swing performance is highly dependent on technical proficiency and kinetic-chain coordination, whereas the present intervention primarily involved bench press and lying overhead triceps extension and did not directly train trunk rotation, shoulder internal rotation, or the complete spiking kinetic chain. General upper-limb strength gains may therefore not transfer completely or proportionally to arm-swing velocity.

4.3. Effects of the Training Protocols on the Dominant-Arm Single-Arm Medicine Ball Throw

Dominant-arm single-arm medicine ball throw distance improved significantly in all four groups. BFRT-140 showed the largest improvement and was significantly superior to BFRT-100. Compared with peak wrist velocity, the single-arm medicine ball throw involves a larger external resistance and a more pronounced force–velocity demand, integrating explosive output from the shoulder, elbow, and trunk kinetic chain. Medicine ball throwing is commonly used to assess upper-limb power in athletes, although performance is also influenced by throwing technique, trunk contribution, release angle, and anthropometric characteristics^[39, 40].

The greater improvement in BFRT-140 than in BFRT-100 suggests that the restriction stimulus produced by 100 mmHg may not have been sufficient to maximize power adaptation at 30% 1RM, whereas increasing pressure to 140 mmHg may have enhanced local metabolic stress and motor-unit recruitment. Although low-load BFRT uses a relatively small external load, the restriction of venous return and accumulation of fatigue may progressively increase the muscle-fiber recruitment required to maintain repeated contractions^[36, 41]. Previous work has shown that different relative restriction pressures can alter acute muscle activation and perceptual responses under the same low-load condition, although long-term adaptation does not necessarily increase linearly with pressure^[41].

Importantly, BFRT-140 was not significantly superior to BFRT-180 or HLRT. Thus, the present results support a greater benefit for throwing performance at 140 versus 100 mmHg but do not establish 140 mmHg as an optimal pressure. BFRT-180 may have provided an effective stimulus comparable to that of 140 mmHg; alternatively, any additional metabolic stimulus at the higher pressure may have been partly offset by greater discomfort or reduced movement quality.

4.4. Effects of the Training Protocols on Bench Press 1RM

Bench press 1RM increased significantly in all four groups, indicating that both low-load BFRT at 30% 1RM and traditional HLRT at 70% 1RM improved maximal dynamic upper-limb strength. Previous upper-limb BFRT studies have shown that low-load restricted bench press training can increase bench press 1RM and may promote adaptations in muscles located both distal and proximal to the cuff^[42, 43]. Systematic-review evidence also suggests that upper-limb low-load BFRT may produce greater strength and morphological adaptations than non-restricted training performed at the same low load, although certainty in the available evidence remains limited^[44].

In the present study, bench press 1RM increased by an average of 8.50 kg in HLRT, and this improvement was significantly greater than that in BFRT-100, although it did not differ significantly from BFRT-140 or BFRT-180. Traditional high-load training has strong movement- and load-specificity for maximal strength development. The bench press 1RM test requires high neural drive, intramuscular coordination, and mechanical tension under large external loads; therefore, the HLRT group, which trained at 70% 1RM, had greater task specificity for the strength test. Meta-analytic evidence generally indicates that both low-load BFRT and high-load training promote muscular adaptations, but high-load training tends to produce greater gains in maximal strength, whereas hypertrophic outcomes may be more comparable^[45].

The bench press 1RM improvement in BFRT-180 was second only to that in HLRT, and no clear difference was observed between these groups. This suggests that training at 30% 1RM with a relatively high fixed pressure may produce practically meaningful strength gains while reducing external mechanical load. Conversely, the smaller improvement in BFRT-100 than in HLRT may indicate that, with a 6-cm cuff, 30% 1RM load, and the present training volume, 100 mmHg did not provide a sufficient additional stimulus to fully compensate for the difference in mechanical tension between low- and high-load training. However, because no pairwise comparison among the three BFRT groups reached statistical significance, a consistent pressure–adaptation relationship for bench press strength cannot be confirmed.

4.5. Effects of the Training Protocols on Upper-Arm Circumference

Bilateral upper-arm circumference increased overall in all four groups, with more pronounced changes in the higher-pressure BFRT conditions. The increase in left upper-arm circumference was greater in BFRT-180 than in BFRT-100 and HLRT, whereas increases in right upper-arm circumference were greater in BFRT-140 and BFRT-180 than in BFRT-100. These findings are broadly consistent with previous evidence that low-load BFRT can promote muscular morphological adaptations. Local hypoxia, metabolite accumulation, cell swelling, and the combined effects of mechanical tension and metabolic stress during low-load BFRT may contribute to muscle-protein synthesis and longer-term morphological adaptation^[36, 37].

Yasuda et al. reported that low-load restricted bench press training induced morphological and strength adaptations not only in the triceps brachii distal to the cuff but also in the pectoralis major proximal to the cuff^[42]. A systematic review of upper-limb BFRT similarly suggested that muscles proximal to the cuff may benefit from low-load BFRT, although substantial heterogeneity exists in training load, pressure prescription, measurement methods, and participant characteristics^[44]. The present intervention included both bench press and lying overhead triceps extension, which directly stimulated the triceps brachii and may help explain the observed increases in upper-arm circumference.

The more pronounced circumference changes in the higher fixed-pressure groups may indicate that, with the 6-cm cuff and 30% 1RM load used in this study, 140–180 mmHg produced a more substantial metabolic stimulus. Nevertheless, previous research does not consistently support the premise that higher pressure necessarily produces greater muscular adaptation. Counts et al. found that restriction pressure influenced acute muscle activation and perceptual responses but did not produce a clear linear pressure dependence in long-term strength or muscle growth^[41]. Lixandrão et al. likewise suggested that occlusion pressure and exercise load may interact to influence adaptation and that increasing pressure alone does not necessarily enhance training outcomes^[45].

Upper-arm circumference is not a direct measure of muscle hypertrophy. Tape-measured circumference is influenced by muscle volume, subcutaneous fat, hydration status, post-exercise edema, and measurement error. Short-term increases in muscle thickness after low-load BFRT may include an

edema component; therefore, an increase in circumference alone cannot be interpreted as definitive evidence of muscle-fiber hypertrophy^[46]. In the present study, post-testing was performed at least 48 h after the final training session, which may have reduced the influence of acute hyperemia, but it could not fully distinguish hypertrophy from changes in tissue fluid.

The patterns of change differed to some extent between the left and right upper arms. This may reflect baseline morphological and usage characteristics developed through long-term dominant-side spiking in volleyball players. Although the intervention involved bilateral symmetrical training, individual baseline status and habitual sport-specific activity may still have influenced the side-specific results. The bilateral findings should therefore be interpreted together with the overall pattern of change rather than using one side alone to infer a definitive side-specific physiological adaptation.

4.6. Relationship Between Fixed Pressure and Training Adaptation

Across the five outcomes, no uniform linear pressure–response pattern was observed. BFRT-140 showed comparatively favorable changes in arm-swing velocity and medicine ball throw distance, whereas BFRT-180 showed larger changes in bench press strength and upper-arm circumference. This pattern suggests that the most effective stimulus may differ across outcomes. Rapid sport-specific actions may depend more strongly on neuromuscular coordination and movement quality, whereas circumference and maximal strength may be more responsive to accumulated metabolic stress and mechanical stimulation.

The present study used fixed absolute pressures of 100, 140, and 180 mmHg rather than individualized percentages of arterial occlusion pressure. The same absolute pressure may produce different degrees of blood flow restriction across participants because actual occlusion is influenced by cuff width, upper-arm circumference, blood pressure, and vascular characteristics^[47]. Accordingly, the findings should be interpreted as a comparison of adaptations to three fixed device-pressure settings.

4.7. Practical Implications

For collegiate volleyball players who require control of external mechanical loading, low-load BFRT at 30% 1RM may serve as an adjunct rather than a complete replacement for traditional high-load strength training. When the primary objective is to increase maximal bench press strength, traditional training at 70% 1RM appears to provide a larger benefit. When the objectives include developing unilateral upper-limb power, maintaining a low external load, and promoting upper-arm morphological adaptation, fixed-pressure BFRT at 140–180 mmHg may offer practical value.

In practice, cuff pressure and exercise load should be selected according to the training objective rather than on the assumption that higher pressure is always more effective. Higher pressures may increase local discomfort and training burden and did not confer a clear additional advantage for arm-swing velocity. Low-load BFRT may be considered as supplementary training during periods of congested

competition, return from injury, or reduced tolerance for joint loading, whereas a proportion of traditional moderate- to high-load training should be retained during phases focused on maximal strength development.

4.8. Limitations

A notable feature of the present study was the comparison of long-term adaptations to three fixed absolute cuff pressures (100, 140, and 180 mmHg) under an otherwise identical low-load training protocol, providing practical evidence regarding fixed-pressure prescription for upper-limb strength and sport-specific performance. However, pressure was not standardized to each participant's arterial occlusion pressure; consequently, the same absolute pressure may have produced different actual degrees of blood flow restriction among participants. The findings are therefore best interpreted as a comparison of three fixed device-pressure protocols. In addition, although the sample size met the a priori power requirement, each group included only eight participants, which may have limited the precision of some between-group estimates; replication in larger samples is warranted. Finally, the participants were male collegiate volleyball players, and the findings should not be directly generalized to female athletes, professional players, or rehabilitation populations.

5. Conclusion

Eight weeks of low-load BFRT and traditional HLRT improved upper-limb strength, power, arm-swing velocity, and upper-arm circumference in male collegiate volleyball players, although the relative advantages of the protocols were outcome-specific. BFRT-140 showed a comparatively favorable effect on single-arm medicine ball throw performance, HLRT was more favorable for improving bench press 1RM, and higher fixed cuff pressures were associated with greater upper-arm circumference adaptations. Overall, low-load BFRT may serve as an effective adjunct to traditional high-load resistance training, but no fixed pressure demonstrated a clear advantage for sport-specific arm-swing velocity.

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with the ethical principles of the Declaration of Helsinki. Ethical approval was obtained from the Ethics Committee of Guangzhou Sport University before the start of the study (Approval No.: 2025LCLL-124, September 15, 2025). Written informed consent was obtained from all participants before participating in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

MY and ZW conceived and designed the study, collected the data, performed the statistical analysis, and drafted the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

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

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Figures

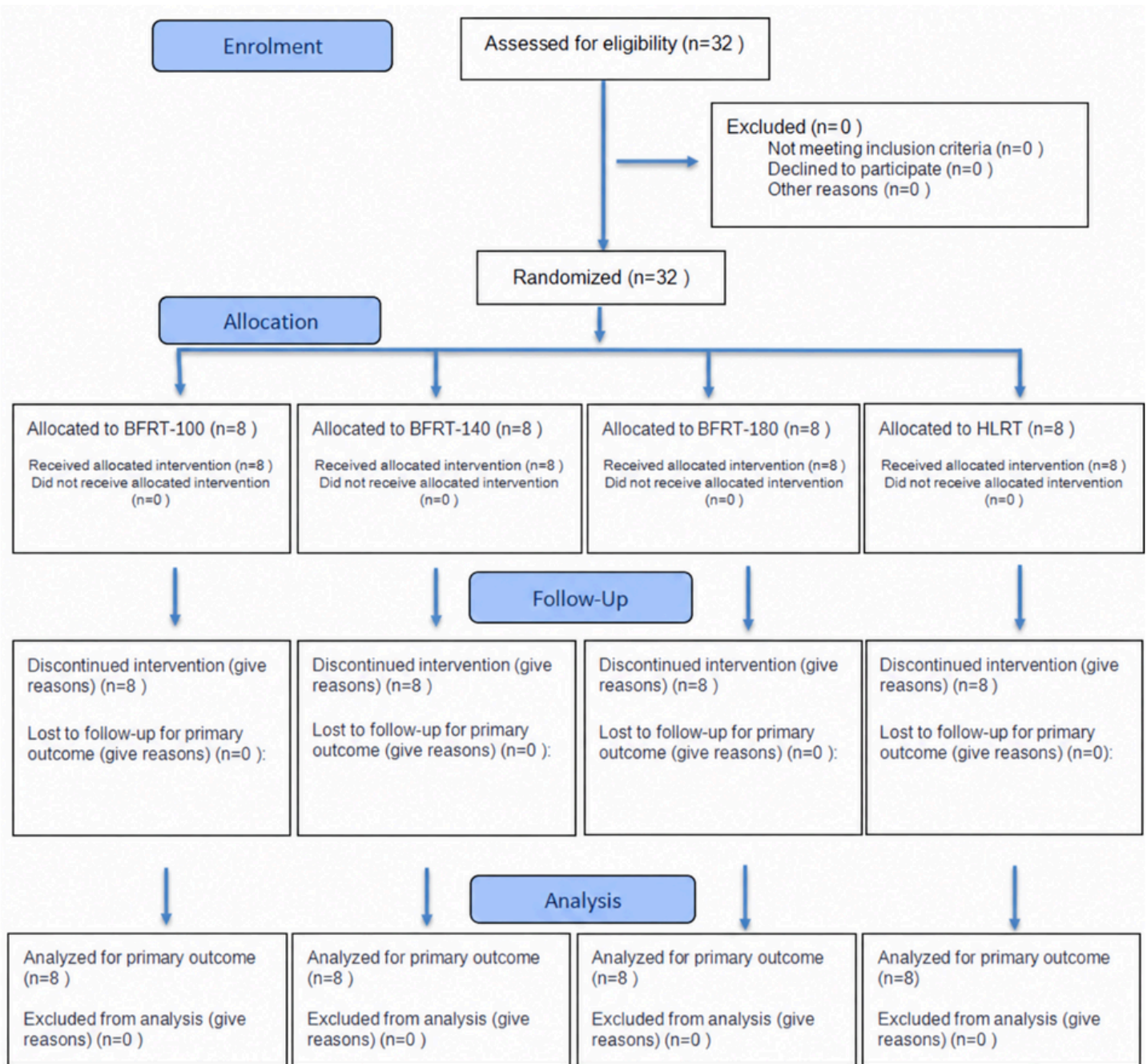


Figure 1

Flowchart for screening, recruitment, allocation, intervention, and follow-up.

Experimental Flowchart

Effects of Fixed-Pressure Blood Flow Restriction Training on Upper-Limb Performance in Male Collegiate Volleyball Players

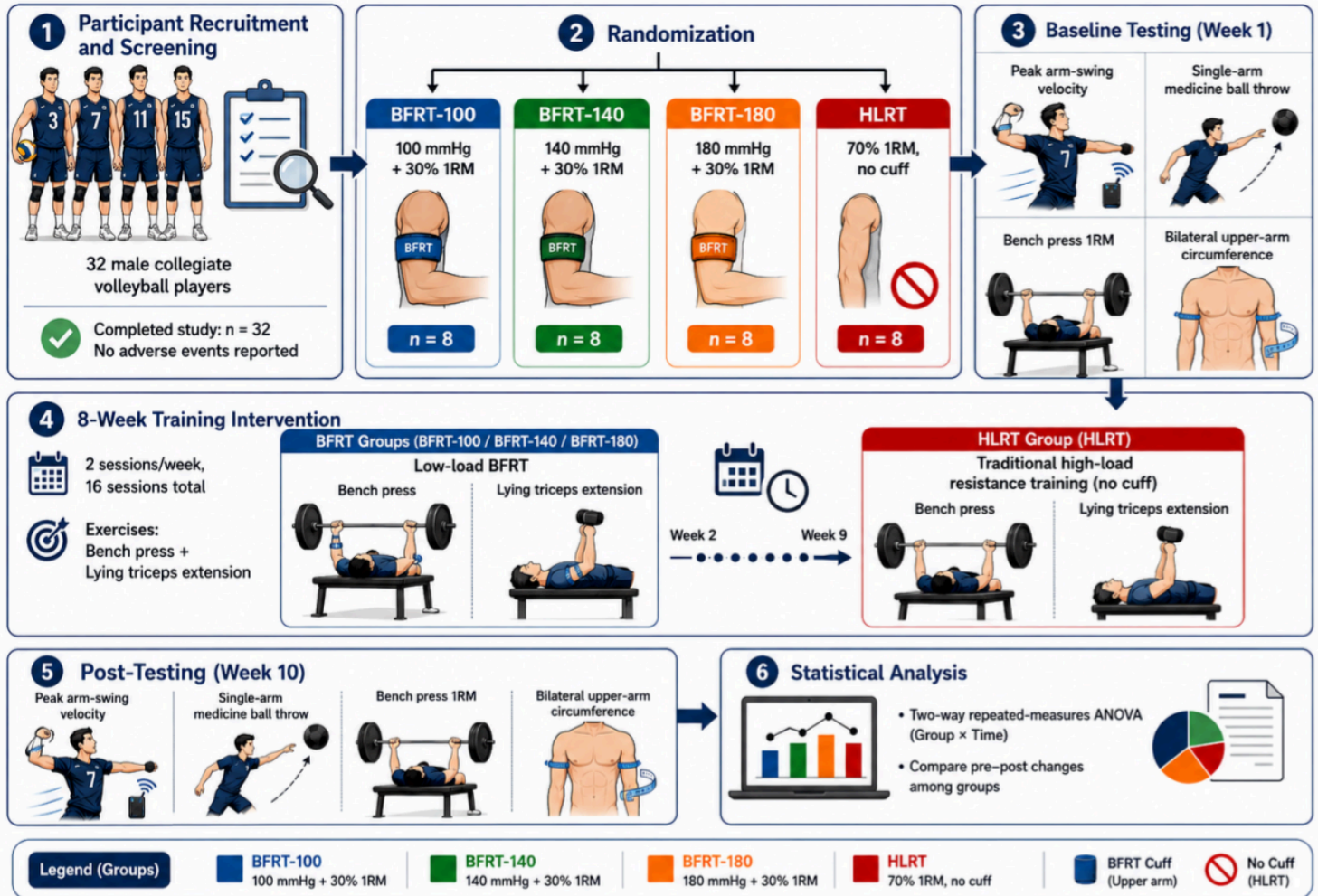


Figure 2

Experimental flowchart.

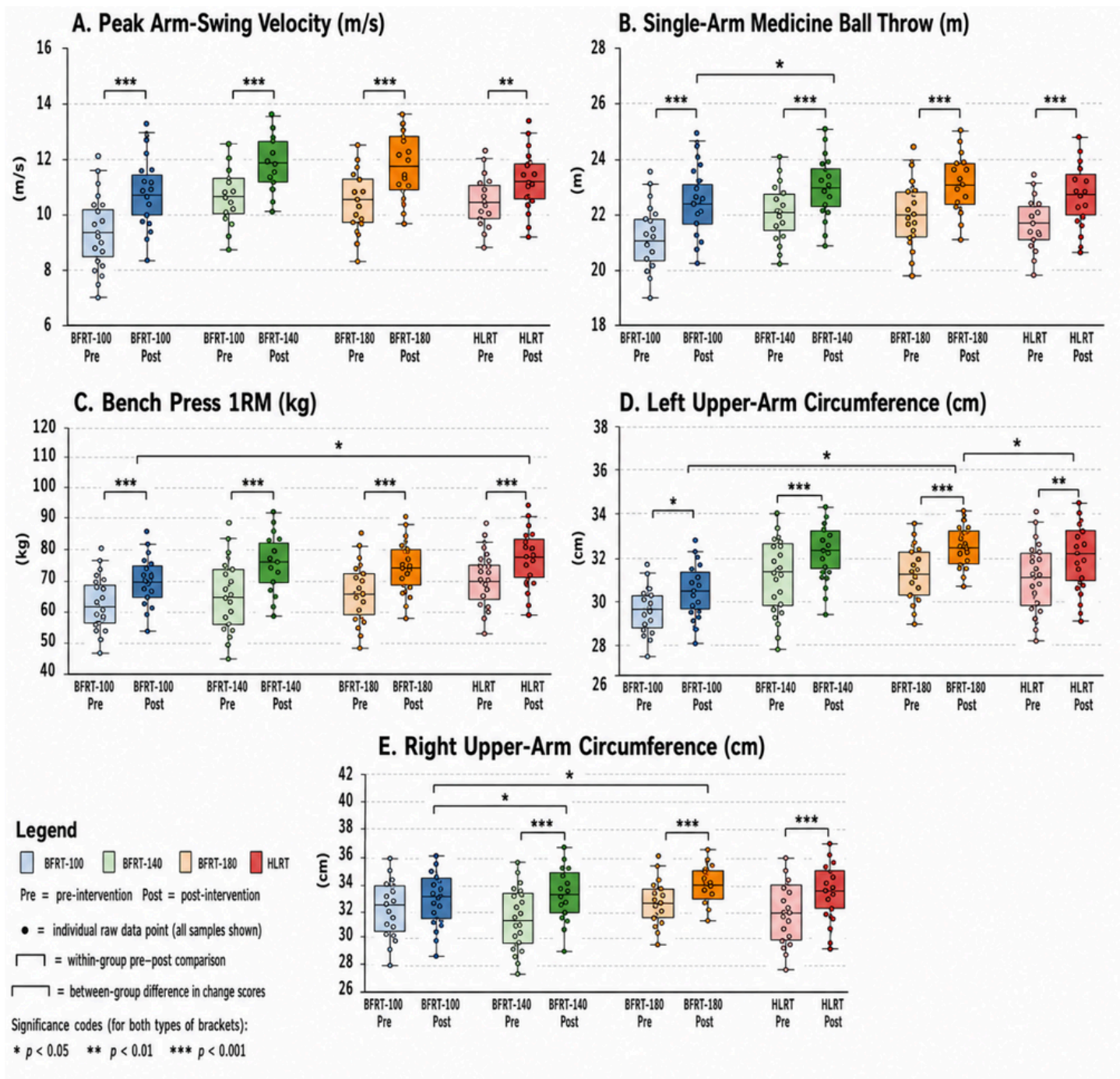


Figure 3

4. Pre- and post-intervention changes in upper-limb performance and upper-arm circumference across training groups. Panels show (A) peak wrist velocity during the arm swing, (B) dominant-arm single-arm medicine ball throw distance, (C) bench press one-repetition maximum (1RM), (D) left upper-arm circumference, and (E) right upper-arm circumference. Boxes represent the interquartile range, horizontal lines indicate the median, diamonds indicate the mean, whiskers extend to 1.5 times the interquartile range, and individual points show raw observations. Asterisks indicate statistically significant within-group pre-post changes or between-group differences in change scores after Bonferroni correction (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

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