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Original Article

Comparative Effects of Low-Load Resistance Exercise with Blood Flow Restriction Versus High-Load Resistance Training on Wrist and Grip Strength and Forearm Hypertrophy in Male University Students: A Randomized Controlled Trial

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ABSTRACT

Background: Blood flow restriction training permits resistance exercise at comparatively low external loads and may therefore provide a practical alternative when reduction of mechanical loading is desirable. Evidence specifically examining wrist and forearm musculature remains limited. Objective: To compare low-load blood flow restriction training with high-intensity resistance training for grip strength, multidirectional wrist strength, and forearm circumference in healthy male university students. Methods: In this parallel-group randomized controlled trial, 45 participants were randomized to BFRT (n=22) or HIRT (n=23). BFRT was performed at 20–30% of estimated 1RM with 50% limb occlusion pressure, whereas HIRT was performed at approximately 80% 1RM. Training was conducted three times weekly for eight weeks. Forty-two participants completed baseline, post-intervention, and four-week follow-up assessments and were analysed per protocol. Outcomes were analysed using 2×3 mixed-model ANOVA. Results: Grip strength increased from 34.75±3.00 to 40.78±3.24 kg in BFRT and from 33.90±2.77 to 40.07±2.73 kg in HIRT. The Group×Time interaction for grip strength was not significant (p=0.893). Interactions were also non-significant for wrist flexion (p=0.912) and extension (p=0.885). Radial and ulnar deviation and forearm circumference increased over time in both groups. Conclusion: Both interventions produced substantial strength improvements. No differential longitudinal response was detected for the reported primary interaction analyses; therefore, the findings support BFRT as a lower-load strengthening strategy without establishing formal equivalence or non-inferiority to HIRT. Keywords: blood flow restriction; resistance training; grip strength; wrist strength; forearm circumference; randomized controlled trial.

INTRODUCTION

Muscular strength is a fundamental determinant of physical performance, functional independence, rehabilitation outcomes, and resistance to musculoskeletal injury. Reliable assessment and progressive development of muscular strength are therefore central components of exercise prescription and rehabilitation practice (1). Within the upper extremity, the wrist flexors, extensors, radial and ulnar deviators, and associated forearm musculature contribute to grip generation, hand stabilization, fine motor control, load transfer, and performance of occupational,

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recreational, and sporting activities. Grip and wrist strength are particularly relevant in young adults who participate in academic, occupational, and recreational activities requiring repeated hand use, sustained gripping, lifting, or upper-extremity loading (2). Identifying effective strategies for strengthening these relatively small muscle groups while minimizing unnecessary mechanical loading is consequently important to both rehabilitation and exercise science.

Blood flow restriction (BFR) training has emerged as an alternative resistance-training strategy in which comparatively low external loads are combined with externally applied limb pressure. The external cuff partially restricts venous return while maintaining sufficient arterial inflow, thereby creating a localized physiological environment characterized by reduced oxygen availability and increased metabolic stress (3). Conventional high-load resistance training generally relies on comparatively large mechanical loads to stimulate strength and muscle adaptation, whereas low-load BFR training is commonly performed at approximately 20–30% of one-repetition maximum (1RM). The physiological conditions generated by BFR allow low-load exercise to produce substantial neuromuscular and morphological responses despite the reduced external resistance (3,4).

Several mechanisms have been proposed to explain these adaptations. Partial restriction of venous outflow facilitates accumulation of lactate, hydrogen ions, inorganic phosphate, and other exercise-related metabolites within the working musculature. The resulting metabolic stress can contribute to anabolic signalling, altered motor-unit recruitment, cellular swelling, and stimulation of pathways associated with muscle protein synthesis (4,5). During unrestricted low-intensity exercise, lower-threshold motor units and predominantly slow-twitch fibres are recruited initially. Under conditions of reduced oxygen availability, however, accelerated fatigue of these fibres may increase recruitment of higher-threshold motor units despite the relatively low external load. This mechanism provides a physiological basis for strength adaptation during BFR exercise performed at intensities substantially below those traditionally used for high-load resistance training (5,6).

The neuromuscular response to BFR is not limited to muscle size. Exercise-induced metabolic stress, altered afferent feedback, and increased recruitment requirements may influence neural drive and motor-unit behaviour. Contemporary experimental work has demonstrated that BFR can modify motor-unit firing and excitation during resistance exercise, supporting the possibility that early strength gains may partly reflect neural adaptation before substantial structural hypertrophy occurs (7,8). These adaptations are especially relevant when considering smaller upper-extremity muscle groups, for which increases in external resistance may be constrained by joint tolerance, tendon loading, exercise technique, or the relatively limited size of the involved musculature.

High-load resistance training remains an established approach for improving muscular strength and mass, and greater mechanical loading generally produces robust strength adaptations. Nevertheless, systematic evidence indicates that low-load BFR can produce meaningful improvements in strength and muscle size, although maximal strength gains may remain greater with conventional high-load resistance exercise in some populations and protocols (6,9). Evidence specifically examining upper-extremity BFR has also demonstrated improvements in strength and morphological outcomes, supporting its potential application beyond the larger lower-limb muscle groups on which much of the original BFR literature was based (10). Systematic reviews comparing blood-flow-restricted exercise with conventional resistance exercise in musculoskeletal populations similarly indicate that BFR can provide clinically relevant strength adaptations while requiring substantially lower external loads (11).

The distinction between comparable improvement and statistical equivalence is important. Available meta-analytic evidence suggests that low-load BFR can produce strength and muscle adaptations of clinically useful magnitude, but the magnitude of the response depends on training load, cuff pressure, muscle group, participant characteristics, intervention duration, and comparison condition (9–12). Consequently, BFR should not be assumed to be universally equivalent or superior to high-load resistance training. Instead, it represents a distinct training stimulus that may be particularly useful when lowering mechanical loading is desirable while maintaining sufficient metabolic and neuromuscular demand.

The practical implementation of BFR depends not only on exercise intensity but also on the method used to apply and quantify external pressure. Commercial systems such as pneumatic tourniquet devices and dedicated BFR cuffs permit standardized pressure control, but access to such equipment can be limited in lower-resource clinical and educational settings. Several forms of external restriction have therefore been used in practice, including pneumatic cuffs, tourniquet systems, elastic restriction devices, and conventional blood-pressure cuffs (13). A

standard sphygmomanometer offers a relatively accessible means of applying measurable external pressure, although the relationship between applied cuff pressure and vascular occlusion varies according to cuff dimensions, limb characteristics, body position, and individual vascular responses. Experimental comparisons indicate that conventional sphygmomanometer cuffs can produce substantial brachial artery restriction and therefore require individualized pressure determination rather than arbitrary fixed inflation values (14).

This issue is particularly important because BFR pressure should be individualized to the participant rather than prescribed solely as an absolute cuff pressure. Limb occlusion pressure or arterial occlusion pressure provides a physiological reference from which the exercise pressure can be expressed as a percentage. Personalized pressure prescription reduces variability caused by individual limb dimensions and vascular characteristics and is recommended to improve both standardization and safety (3). The present study therefore employed a protocol in which BFR training pressure was prescribed relative to individually determined limb occlusion pressure rather than using the same absolute pressure for every participant.

Although BFR research has expanded considerably, the evidence remains disproportionately concentrated on larger muscles of the thigh and upper arm. Research specifically involving the wrist and forearm musculature is considerably more limited (10,15). This is an important gap because the forearm contains relatively small but functionally important muscle groups involved in wrist flexion, wrist extension, radial and ulnar deviation, and grip stabilization. Upper-extremity BFR studies have generally evaluated elbow flexors, upper-arm musculature, grip-related performance, or broader upper-limb outcomes rather than a comprehensive set of isolated wrist movements (10,15).

Evidence from athletic populations further supports investigation of upper-extremity BFR. Low-load BFR has been associated with improvements in upper-body strength and sport-specific force production in trained participants, including elite athletes, demonstrating that its application is not limited to clinical rehabilitation populations (17). Meta-analytic work has also demonstrated performance adaptations after BFR resistance exercise, although responses vary according to outcome and muscle group (18). Clinical and case-based observations involving wrist conditions suggest potential utility in upper-extremity rehabilitation, but such evidence cannot be directly generalized to healthy young adults (19). More recent syntheses of upper-limb BFR likewise indicate measurable acute and training-related effects on upper-extremity strength while emphasizing heterogeneity between protocols (20).

Safety and pressure monitoring remain central considerations in BFR prescription. Adverse responses reported with appropriately prescribed BFR are generally transient and minor, but excessive or poorly controlled restriction can produce discomfort, numbness, paresthesia, or undesirable vascular stress. Methodological recommendations therefore emphasize participant screening, individualized occlusion pressure, appropriate cuff inflation, monitoring during exercise, and prompt cuff release when indicated (21). Doppler-based assessment is widely used for arterial occlusion pressure determination, and handheld Doppler systems have been investigated as practical methods of assessing brachial and femoral artery occlusion pressure (22). However, Doppler equipment may not be readily available in every rehabilitation or teaching environment.

Alternative approaches have therefore been investigated. Comparative studies of BFR devices demonstrate that pressure requirements and occlusion behaviour differ between devices and body positions, reinforcing the need for individualized assessment rather than device-independent pressure assumptions (23). Pulse oximetry has also been investigated as an accessible method for supporting arterial occlusion pressure determination and distal perfusion monitoring, with strong agreement reported against handheld Doppler methods in relevant experimental settings (24). These approaches are particularly relevant in settings where dedicated BFR systems are financially difficult to obtain.

Accurate outcome measurement is equally important. Hand-held dynamometry is widely used for quantifying upper-extremity strength and has demonstrated acceptable to excellent reliability when testing position, stabilization, assessor technique, and instructions are standardized (25,26). Grip dynamometry provides an objective measure of handgrip force, whereas wrist flexion, extension, and deviation strength can be assessed through resistance-based testing. Where direct maximal testing is undesirable or technically difficult, estimated 1RM can be obtained from submaximal repetitions using established prediction equations. The Brzycki equation is a commonly used approach for estimating 1RM from repetitions performed with a submaximal load (27,28).

Forearm circumference provides a simple anthropometric indicator of change in forearm size. Tension-regulated anthropometric tapes can improve consistency by reducing variation in tape tension and tissue compression, and standardized landmarks are important when measurements are repeated longitudinally (29). Circumference, however, represents total limb girth and cannot distinguish skeletal-muscle hypertrophy from changes in subcutaneous tissue, fluid, or other components. It is therefore more appropriately interpreted as an anthropometric indicator of forearm-size change rather than a direct measurement of muscle cross-sectional area.

Pressure individualization, participant characteristics, and training prescription may influence the magnitude of adaptation to BFR. Current evidence emphasizes the importance of prescribing restriction according to an individual physiological pressure reference rather than applying uniform pressures across participants (30). Studies in young men have further demonstrated that BFR can influence exercise performance and physiological responses, supporting the relevance of investigating standardized BFR protocols in healthy young adult populations (31). Within Pakistan, clinical investigation has also begun to evaluate BFR as a low-load strengthening strategy. An RCT among individuals with early knee osteoarthritis reported strength improvements following low-load BFRT and supported its use as a potential resistance-training option when high mechanical loading is difficult to tolerate (32). However, lower-limb findings cannot be assumed to represent responses of the wrist and forearm.

A particular evidence gap therefore exists regarding low-load BFR applied specifically to wrist and forearm strengthening in healthy Pakistani university students using accessible equipment. The combination of a standard sphygmomanometer, physiological pressure individualization, pulse-oximetry-based monitoring, grip dynamometry, submaximal wrist-strength testing, and anthropometric forearm assessment provides a pragmatic model that may be feasible in teaching and rehabilitation environments where specialized BFR systems are unavailable. Investigation of such a protocol is relevant not only to the physiological efficacy of BFR but also to its practical implementation under lower-resource conditions.

The objective of this randomized controlled trial was therefore to compare the effects of eight weeks of low-load resistance exercise performed with blood flow restriction at 20–30% of estimated 1RM and 50% of limb occlusion pressure with conventional high-load resistance training performed without blood flow restriction in healthy male university students. The principal outcomes were grip strength, wrist flexion strength, wrist extension strength, radial deviation strength, and ulnar deviation strength, while forearm circumference was evaluated as an anthropometric indicator of change in forearm size. It was hypothesized that the pattern of change in these outcomes would differ between the BFRT and HIRT groups over the baseline, post-intervention, and follow-up assessments.

MATERIALS AND METHODS

The study was conducted as a parallel-group randomized controlled trial with repeated longitudinal assessment. The analytical structure comprised a 2 × 3 mixed-factorial design, with training group as the between-participant factor and time as the within-participant factor. Participants were evaluated at baseline, immediately after completion of the eight-week intervention, and again four weeks after completion of training. The design allowed comparison of longitudinal adaptation to low-load blood flow restriction training and high-intensity resistance training while maintaining randomized allocation between the two parallel intervention groups. Randomized parallel-group methodology was implemented in accordance with established principles for reducing systematic allocation differences between intervention groups (33).

The study was conducted at the Rehabilitation and Research Center of the Lahore Institute of Professional Studies, Lahore, Pakistan. The intervention itself lasted eight weeks and was followed by a four-week post-intervention follow-up. Healthy recreationally active male university students in Lahore constituted the target population. Recruitment used purposive screening to identify eligible participants, whereas assignment to the intervention groups was subsequently performed through randomized allocation. This distinction was maintained because participant recruitment and treatment allocation represented separate methodological stages.

Potential participants underwent eligibility screening using the Physical Activity Readiness Questionnaire and the study-specific screening criteria. The PAR-Q was used to identify cardiovascular, musculoskeletal, neurological, or exercise-related conditions that might contraindicate participation in resistance or BFR exercise, consistent with its role as a pre-participation exercise-screening instrument (34). Eligible participants were male university

students aged 18–26 years who were cleared by the PAR-Q, had no chronic disease or upper-limb deformity, and were willing to participate after providing informed consent.

Participants were excluded if they had experienced an upper-limb or wrist injury or trauma within the preceding six months; were currently participating in structured forearm-strength training; had a history of hypertension, peripheral vascular disease, thrombosis or embolism, ischemic heart disease, myocardial infarction, or another relevant cardiovascular disorder; had rheumatoid arthritis, avascular necrosis, peripheral neuropathy, diabetes, fibromyalgia, active cancer, severe obesity, amputation, or a blood-clotting disorder; were current smokers; had unexplained fainting or dizziness associated with exercise or loss of balance; or had used medications known to influence muscle mass or performance during the preceding six months. These criteria were used to establish a relatively homogeneous healthy sample and to minimize foreseeable risks associated with high-intensity exercise or vascular restriction.

A total of 45 eligible participants were enrolled. An a priori sample-size assessment was undertaken using G*Power version 3.1.9.7, an established statistical power-analysis program (35). The recorded calculation used an alpha level of 0.05, statistical power of 80%, an effect-size input of 0.94, and an intended allocation ratio of approximately 1:1, yielding an estimated minimum total sample of 38 participants. Forty-five participants were enrolled, providing additional capacity for attrition during the intervention and follow-up period.

After completion of baseline assessment, participants were randomized using a computer-generated random-number sequence. Allocation assignments were placed in sealed envelopes and remained concealed until the baseline measurements had been completed. Twenty-two participants were allocated to the low-load blood flow restriction training group and 23 to the high-intensity resistance training group. The BFRT group performed low-load resistance exercise at 20–30% of estimated 1RM with the cuff pressure set at 50% of individually determined limb occlusion pressure. The HIRT group performed resistance exercise without vascular restriction using approximately 80% of estimated 1RM.

Grip strength was assessed using a hand-held grip dynamometer. Dynamometric measurement provides an objective method of quantifying grip force and demonstrates good reliability when standardized testing positions and procedures are maintained (25,26,36,37). For grip testing, participants were positioned with the shoulder adducted and neutrally rotated, the elbow flexed to 90°, the forearm in a neutral position, and the wrist maintained within approximately 0–30° of extension. Three trials were available for recording, with the mean and best values documented. Standardization of participant positioning and assessor technique was used to reduce measurement variability.

Wrist flexion, wrist extension, radial deviation, and ulnar deviation strength were evaluated using submaximal resistance testing with free weights and estimation of 1RM. Participants were seated with the tested forearm supported and stabilized on a table, the elbow flexed to approximately 90°, and the wrist positioned just beyond the edge of the support to permit unrestricted movement. The forearm was supinated for wrist-flexion testing and pronated for wrist-extension testing. Radial and ulnar deviation were evaluated using the corresponding movements toward the thumb and little-finger sides of the wrist. Multiple attempts could be performed, with two to three minutes of rest between attempts. The best valid submaximal performance and completed repetitions were used to estimate 1RM using the Brzycki prediction approach (27,28). Contemporary validation work supports the use of submaximal prediction equations for estimating resistance-training strength when standardized loading and repetition procedures are used (39).

Forearm circumference was assessed with a tension-regulated Gulick anthropometric tape. Measurements were performed at a standardized landmark 10 cm distal to the lateral epicondyle with the arm relaxed and supinated. The measurement landmark was marked to facilitate repeated assessment at the same anatomical location. Three circumference measurements could be recorded and averaged. Standardized anthropometric procedures and controlled tape tension reduce measurement error during repeated girth assessment (29). Because circumference represents total forearm girth, this measure was interpreted as an anthropometric indicator of forearm-size change rather than a direct measurement of skeletal-muscle cross-sectional area.

A sphygmomanometer cuff was used to apply external pressure in the BFRT group. Individual limb occlusion pressure was recorded in millimetres of mercury, and the training pressure was prescribed as 50% of the

participant-specific occlusion pressure rather than as a uniform absolute cuff pressure. Individualization of restriction pressure is recommended because the degree of vascular restriction produced by a given absolute pressure varies between participants and devices (3,21–24). Pulse oximetry was incorporated for distal perfusion and safety monitoring during the BFR protocol. Pulse-oximetry-based approaches have demonstrated utility for supporting occlusion-pressure assessment and monitoring, although the physiological meaning of the measurement remains dependent on standardized placement and interpretation (24,38).

The intervention was conducted three times per week for eight weeks, with sessions scheduled on non-consecutive days to provide at least approximately 48 hours between training exposures. Each session followed a standardized sequence consisting of warm-up, execution of the assigned resistance-training protocol, prescribed inter-set rest intervals, safety monitoring, and cool-down. The warm-up lasted approximately five minutes and included 15 slow wrist rotations in both clockwise and counterclockwise directions, 15 rapid finger opening-and-closing movements, and one set of 15 wrist curls using a 1-kg dumbbell. Participants were then seated with the forearm horizontally supported on a padded surface and the wrist free to move beyond the edge of the support.

Participants in the BFRT group exercised at 20–30% of estimated 1RM while the cuff was maintained at 50% of individual limb occlusion pressure. The BFRT repetition scheme consisted of 75 total repetitions distributed across four sets: 30 repetitions in the first set followed by three sets of 15 repetitions. Inter-set recovery was 30 seconds, and the cuff remained inflated during these short inter-set intervals. The cuff was released immediately after completion of the final set. Distal circulation, participant symptoms, and reactive hyperemia after cuff release were monitored as safety indicators. This type of high-repetition, low-load approach is consistent with established methodological principles for BFR resistance exercise (21).

Participants in the HIRT group exercised without a cuff using approximately 80% of estimated 1RM. The high-load protocol consisted of three sets of 10 repetitions, yielding 30 total repetitions, with approximately 120 seconds of passive recovery between sets. The HIRT protocol therefore emphasized comparatively greater mechanical resistance, whereas the BFRT protocol combined lower mechanical load with greater repetition volume and partial vascular restriction.

Perceived exercise intensity was monitored after the final repetitions using a Borg rating-of-perceived-exertion scale. This measure was used for session monitoring rather than as a primary study outcome. Following exercise, participants performed forearm-flexor and forearm-extensor stretches for two sets of 30 seconds each. The BFRT cuff was completely deflated before the cool-down period.

Measurement and data-quality procedures were standardized across assessment occasions. The study assessment protocol included equipment checks for the dynamometer, pulse oximeter, and sphygmomanometer; use of the same assessor where feasible; assessment at a similar time of day; avoidance of strenuous exercise during the preceding 24 hours; avoidance of caffeine during the three hours preceding testing; standardized warm-up; standardized verbal encouragement; and consistent ordering of testing. Data were double-checked after collection, entered into SPSS, and range-checked as part of the study data-validation process.

The principal strength outcomes were grip strength, wrist flexion strength, wrist extension strength, radial deviation strength, and ulnar deviation strength. Forearm circumference represented the secondary anthropometric outcome. All outcomes were assessed at baseline, immediately after the eight-week training intervention, and at the four-week post-intervention follow-up. This repeated-measures structure permitted assessment of both immediate training-associated changes and short-term maintenance after completion of supervised training.

Statistical analyses were performed using IBM SPSS Statistics version 27.0. Continuous outcomes were summarized using means and standard deviations. Distributional assumptions were evaluated using the Shapiro–Wilk test. Longitudinal differences were assessed using a 2 × 3 mixed-model analysis of variance, with training condition (BFRT versus HIRT) as the between-participant factor and assessment time (baseline, post-intervention, and four-week follow-up) as the repeated within-participant factor. The Group × Time interaction was used to evaluate whether the pattern of change differed between BFRT and HIRT. Mauchly's test was used to evaluate the sphericity assumption. Greenhouse–Geisser correction was applied where the sphericity assumption was violated. Statistical significance was defined as $p<0.05$.

Forty-five participants were randomized, but three did not complete all assessment occasions. One BFRT participant withdrew during week 3 because of scheduling difficulties unrelated to the intervention. In the HIRT group, one participant withdrew during week 2 following a minor wrist strain described as unrelated to the research protocol, and one participant did not return for the four-week follow-up assessment. Consequently, 42 participants completed all three assessment occasions, comprising 21 participants in each group. The primary longitudinal analysis used a per-protocol approach and therefore included participants with complete baseline, post-intervention, and follow-up observations.

All participants entered the study voluntarily and provided informed consent before participation. Exercise screening, individualized restriction pressure, physiological monitoring, adverse-symptom monitoring, and supervised exercise procedures were incorporated to reduce foreseeable risk associated with resistance exercise and blood flow restriction.

RESULTS

Forty-five male university students were randomized, with 22 allocated to BFRT and 23 allocated to HIRT. Forty-two participants completed the intervention and all three assessment occasions, giving an overall retention rate of 93.3%. The per-protocol analysis therefore comprised 21 participants in each group.

Table 1. Participant Flow and Analysis Population

Study stage	BFRT, n	HIRT, n	Total, n
Randomized	22	23	45
Withdrawn/lost to follow-up	1	2	3
Completed post-intervention and follow-up assessment	21	21	42
Included in per-protocol analysis	21	21	42

The distributional assessment supported the use of parametric longitudinal analysis for the majority of outcome measurements. Shapiro–Wilk probabilities exceeded 0.05 for most group-by-time combinations. The notable exception was radial-deviation strength at follow-up in the BFRT group, for which the Shapiro–Wilk test yielded p=0.031. The remaining reported grip, flexion, extension, and ulnar-deviation measurements generally satisfied the normality criterion.

Across the three assessment occasions, both training groups demonstrated increases in grip strength, wrist flexion, wrist extension, radial deviation, ulnar deviation, and forearm circumference relative to baseline. The magnitude and direction of the changes were broadly similar across several strength outcomes, although descriptive differences between groups were present for individual variables.

Table 2. Strength and Forearm-Circumference Outcomes Across Baseline, Post-Intervention, and Follow-Up Assessments

Outcome	Group	Baseline mean ± SD	Post-intervention mean ± SD	4-week follow-up mean ± SD	Baseline-to post change	Baseline-to follow-up change
Grip strength, kg	BFRT	34.75 ± 3.00	40.78 ± 3.24	40.92 ± 3.86	+6.03	+6.17
	HIRT	33.90 ± 2.77	40.07 ± 2.73	39.94 ± 3.67	+6.17	+6.04
Wrist flexion, kg	BFRT	15.16 ± 1.38	19.02 ± 1.57	18.88 ± 1.70	+3.86	+3.72
	HIRT	15.33 ± 1.46	19.53 ± 1.93	19.47 ± 2.28	+4.20	+4.14
Wrist extension, kg	BFRT	12.00 ± 1.22	15.02 ± 1.36	14.73 ± 1.25	+3.02	+2.73
	HIRT	12.40 ± 0.82	15.30 ± 1.00	15.26 ± 1.22	+2.90	+2.86
Ulnar deviation, kg	BFRT	8.23 ± 0.79	10.13 ± 0.88	10.13 ± 0.90	+1.90	+1.90
	HIRT	7.82 ± 0.89	9.93 ± 1.03	10.02 ± 1.14	+2.11	+2.20
Radial deviation, kg	BFRT	9.06 ± 0.87	11.31 ± 0.96	11.37 ± 0.96	+2.25	+2.31
	HIRT	8.94 ± 1.07	11.23 ± 1.25	11.26 ± 1.22	+2.29	+2.32
Forearm circumference, cm	BFRT	24.70 ± 1.02	26.10 ± 1.46	27.06 ± 1.56	+1.40	+2.36
	HIRT	24.80 ± 0.90	26.90 ± 0.96	27.80 ± 0.99	+2.10	+3.00

BFRT: blood flow restriction training; HIRT: high-intensity resistance training; SD: standard deviation.

Grip strength increased from 34.75±3.00 kg at baseline to 40.78±3.24 kg after training and 40.92±3.86 kg at follow-up in the BFRT group. This corresponded to increases of 6.03 kg (17.4%) immediately after training and 6.17 kg (17.8%) at follow-up. In the HIRT group, grip strength increased from 33.90±2.77 kg to 40.07±2.73 kg after training and 39.94±3.67 kg at follow-up, corresponding to changes of 6.17 kg (18.2%) and 6.04 kg (17.8%), respectively. The main effect of time for grip strength was statistically significant ($p<0.001$), while the Group × Time interaction was not significant ($p=0.893$), indicating that the longitudinal pattern of grip-strength change did not differ statistically

between the two training groups. Wrist-flexion strength increased by 3.86 kg from baseline to post-intervention and by 3.72 kg from baseline to follow-up in the BFRT group, representing relative increases of approximately 25.5% and 24.5%. The corresponding increases in the HIRT group were 4.20 kg and 4.14 kg, or approximately 27.4% and 27.0%. The Group × Time interaction for wrist flexion was not statistically significant (p=0.912).

Wrist-extension strength increased from 12.00±1.22 kg to 15.02±1.36 kg after training in the BFRT group and from 12.40±0.82 kg to 15.30±1.00 kg in the HIRT group. At follow-up, mean values remained above baseline in both groups at 14.73±1.25 kg and 15.26±1.22 kg, respectively. Baseline-to-post changes were 3.02 kg (25.2%) for BFRT and 2.90 kg (23.4%) for HIRT. The corresponding follow-up changes were 2.73 kg (22.8%) and 2.86 kg (23.1%). The Group × Time interaction was not statistically significant (p=0.885). Ulnar-deviation strength increased from 8.23±0.79 kg to 10.13±0.88 kg after BFRT and was maintained at 10.13±0.90 kg at follow-up. HIRT increased ulnar-deviation strength from 7.82±0.89 kg to 9.93±1.03 kg after training and 10.02±1.14 kg at follow-up. The baseline-to-follow-up changes were 1.90 kg (23.1%) with BFRT and 2.20 kg (28.1%) with HIRT. A statistically significant effect of time was reported for ulnar-deviation strength (p<0.001).

Radial-deviation strength increased from 9.06±0.87 kg at baseline to 11.31±0.96 kg after BFRT and 11.37±0.96 kg at follow-up. Corresponding HIRT values were 8.94±1.07 kg, 11.23±1.25 kg, and 11.26±1.22 kg. Relative baseline-to-follow-up improvements were approximately 25.5% for BFRT and 26.0% for HIRT. A statistically significant effect of time was reported for radial-deviation strength (p<0.001). Forearm circumference increased progressively across the assessment period. The BFRT group increased from 24.70±1.02 cm at baseline to 26.10±1.46 cm after training and 27.06±1.56 cm at follow-up, yielding absolute changes of 1.40 cm at post-intervention and 2.36 cm at follow-up. The HIRT group increased from 24.80±0.90 cm to 26.90±0.96 cm and 27.80±0.99 cm, producing corresponding changes of 2.10 cm and 3.00 cm. These values represent changes in measured forearm circumference and were not interpreted as direct measurements of muscle cross-sectional hypertrophy.

Table 3. Reported Group × Time Interaction Tests for Principal Strength Outcomes

Outcome	Group × Time p-value
Grip strength	0.893
Wrist flexion	0.912
Wrist extension	0.885

For all three reported interaction tests, p-values exceeded 0.05. Accordingly, the analysis did not identify statistically significant evidence that the trajectory of change differed between BFRT and HIRT for grip strength, wrist flexion, or wrist extension. These non-significant interactions were interpreted as an absence of detected between-group differences in longitudinal response rather than as statistical proof of equivalence or non-inferiority. Mauchly's test indicated violation of the sphericity assumption for grip strength, wrist flexion, wrist extension, and ulnar deviation. Greenhouse–Geisser corrections were therefore applied to these repeated-measures analyses. Radial deviation and forearm circumference did not demonstrate statistically significant departures from sphericity.

Table 4. Mauchly's Test of Sphericity and Greenhouse–Geisser Epsilon

Outcome	Mauchly's W	Approx. χ^2	df	p-value	Greenhouse–Geisser ε
Grip strength	0.570	21.914	2	<0.001	0.699
Wrist flexion	0.650	16.795	2	<0.001	0.741
Wrist extension	0.711	13.286	2	0.001	0.776
Ulnar deviation	0.765	10.460	2	0.005	0.810
Radial deviation	0.865	5.650	2	0.059	0.881
Forearm circumference	0.892	4.320	2	0.115	0.902

Taken together, the longitudinal results demonstrated substantial within-group increases across the measured strength outcomes after eight weeks of training, with most improvements remaining evident at the four-week follow-up. For the three outcomes with explicitly reported interaction probabilities, no statistically significant Group × Time interaction was detected. The findings therefore support improvement under both training protocols while providing no evidence from these interaction tests that either BFRT or HIRT produced a statistically different trajectory of change in grip, flexion, or extension strength.

DISCUSSION

This randomized controlled trial compared eight weeks of low-load resistance training performed with blood flow restriction against conventional high-intensity resistance training in healthy male university students. Both training groups demonstrated substantial increases in grip strength and strength during wrist flexion, extension, radial deviation, and ulnar deviation, and these gains were largely maintained at the four-week follow-up. Forearm circumference also increased over time in both groups. For grip strength, wrist flexion, and wrist extension, the reported Group × Time interactions were not statistically significant, indicating that the study did not detect differential longitudinal responses between BFRT and HIRT for these outcomes. Importantly, these results demonstrate absence of a detected difference rather than formal statistical equivalence or non-inferiority.

The magnitude of improvement observed with BFRT is notable because participants trained using only 20–30% of estimated 1RM, substantially below the mechanical loading used in the HIRT condition. This finding is consistent with the physiological rationale underlying BFR exercise. Restriction of venous outflow during low-load contraction increases local metabolite accumulation and creates a relatively hypoxic intramuscular environment, which can increase motor-unit recruitment and stimulate cellular pathways associated with adaptation (4,5). Accelerated fatigue of lower-threshold fibres may promote earlier recruitment of higher-threshold motor units, thereby allowing low-load contractions to provide a stronger neuromuscular stimulus than comparable low-load exercise performed without vascular restriction (5,6).

The present findings are broadly compatible with systematic evidence demonstrating that low-load BFR improves muscular strength and size compared with low-load exercise alone and can produce adaptations approaching those seen with higher-load resistance training in selected contexts (6,9,11). Centner et al. reported meaningful improvements following BFR exercise across populations in which traditional heavy loading may be less feasible, although the magnitude of maximal-strength adaptation can depend on the comparator and training population (6). Chang et al. similarly demonstrated that low-load BFR can produce substantial muscular adaptation in untrained males when compared with conventional high-load resistance training (9). These findings provide an appropriate framework for interpreting the current trial: BFRT produced substantial improvement despite the use of markedly lower external loads, but the present statistical analysis does not establish that the two interventions are formally equivalent.

Upper-extremity evidence is especially relevant to the current results. A systematic review and meta-analysis of upper-extremity BFR demonstrated improvements in upper-limb muscular strength and hypertrophy-related outcomes, supporting extension of BFR principles beyond the lower extremity (10). The current trial adds a more distal focus by examining grip and several specific wrist movements rather than concentrating primarily on elbow flexors or larger upper-arm muscle groups. The improvements across wrist flexion, extension, radial deviation, and ulnar deviation suggest that the physiological stimulus associated with BFR can be applied to smaller forearm muscle groups when exercise position, loading, and cuff pressure are appropriately controlled.

The grip-strength findings were particularly consistent between groups. BFRT improved mean grip strength from 34.75 to 40.78 kg after training, whereas HIRT increased mean grip strength from 33.90 to 40.07 kg. At follow-up, values remained 40.92 and 39.94 kg, respectively. The Group × Time interaction of $p=0.893$ indicates that no statistically detectable difference in the pattern of grip-strength change emerged between the interventions. This finding aligns with broader upper-extremity literature showing that BFR can influence grip and upper-limb performance (10,20), while also demonstrating that conventional high-load training remains highly effective.

Wrist flexion and extension showed similarly substantial gains. BFRT produced baseline-to-post increases of approximately 25.5% for flexion and 25.2% for extension, whereas HIRT produced increases of approximately 27.4% and 23.4%, respectively. The interaction probabilities of $p=0.912$ for flexion and $p=0.885$ for extension indicate no detectable evidence that the rate of adaptation differed between the groups. These results are physiologically plausible because the BFR condition was designed to increase metabolic demand while reducing external mechanical load. The increased recruitment requirements associated with reduced oxygen availability may compensate, in part, for the lower mechanical stimulus during low-load exercise (5,7,8).

Neuromuscular adaptation provides an additional explanation. Experimental evidence indicates that BFR can alter motor-unit firing and excitation during resistance exercise (8). Such neural changes are particularly relevant during

relatively short training periods because improvements in force production during the initial weeks of resistance exercise are not attributable solely to structural hypertrophy. The preservation of strength improvements at the four-week follow-up in the current study suggests that the adaptations were not limited to an acute post-exercise response.

The results for radial and ulnar deviation extend the evidence to movements that are less frequently examined in BFR research. Both groups demonstrated increases exceeding 20% from baseline across these measures, and significant time effects were reported for both radial and ulnar deviation. Existing literature has primarily emphasized larger muscle groups or broader upper-extremity outcomes (10,15,20). The current results therefore support further examination of BFR for more isolated distal upper-extremity movements, particularly where functional goals involve multidirectional wrist control.

The present findings are also consistent with evidence from athletic populations. Awana et al. demonstrated that BFR could improve upper-body strength and punching-force outcomes in elite boxers despite the use of comparatively low training loads (17). Fekri-Kourabbaslou et al. likewise demonstrated meaningful physiological and performance responses to BFR resistance exercise in young men (31). Although differences in training status, exercises, and outcomes prevent direct comparison, these studies support the broader concept that BFR can provide a meaningful neuromuscular stimulus in young and physically active populations.

The results should nevertheless be interpreted in light of the characteristics of the current sample. Participants were young, healthy, recreationally active male university students. Such individuals may possess sufficient baseline neuromuscular capacity to respond effectively to both low-load BFR and high-load resistance training. This differs from populations with osteoarthritis, postsurgical limitations, pain-related load intolerance, or age-related sarcopenia, for whom reducing mechanical load may provide a greater practical advantage. Shafqat et al. found beneficial effects of low-load BFRT in participants with early knee osteoarthritis, illustrating the potential value of BFR when conventional loading is comparatively difficult to tolerate (32). The present findings extend the investigation to healthy young adults but should not be generalized directly to clinical populations.

Forearm circumference increased in both groups and remained elevated at follow-up. The BFRT group increased by 1.40 cm immediately after the intervention and by 2.36 cm from baseline to follow-up, whereas the HIRT group increased by 2.10 cm and 3.00 cm across the same intervals. These changes demonstrate increased measured forearm girth but should not be interpreted as direct evidence of skeletal-muscle hypertrophy. Circumference is influenced by muscle tissue, subcutaneous tissue, hydration, and other components and does not provide the anatomical specificity of ultrasound or magnetic-resonance assessment. Standardized anthropometric procedures improve measurement reliability, but they do not convert girth measurement into a direct measure of muscle cross-sectional area (29).

The descriptive circumference findings also caution against assuming that low-load BFRT produced greater hypertrophy than HIRT. Indeed, the recorded absolute circumference changes were numerically larger in the HIRT group. The appropriate interpretation is therefore that forearm circumference increased over time under both resistance-training approaches. More direct imaging-based measures would be required to determine whether the interventions produced different changes in muscle thickness or cross-sectional area.

Pressure prescription is another important feature of the trial. The BFRT group trained at 50% of individually determined limb occlusion pressure rather than receiving a fixed absolute cuff pressure. Individualization is consistent with current methodological recommendations because the relationship between absolute cuff pressure and vascular restriction depends on limb size, cuff characteristics, body position, and vascular physiology (3,21). Studies comparing BFR devices further show that different cuff systems can produce different degrees of occlusion at the same nominal pressure (14,23). Using a participant-specific percentage of occlusion pressure therefore strengthens the physiological rationale of the protocol.

The use of a conventional sphygmomanometer is particularly relevant to the local context. Specialized BFR devices can be expensive or inaccessible in lower-resource rehabilitation, educational, and fitness facilities. Standard blood-pressure cuffs provide a comparatively accessible method of delivering measurable external pressure, but their use requires careful physiological calibration and monitoring. O'Connor reported substantial brachial artery occlusion with conventional sphygmomanometer cuffs, emphasizing that these devices should not simply be

inflated to arbitrary pressures (14). Pulse-oximetry-based approaches may provide additional practical support for monitoring distal circulation and determining vascular responses where handheld Doppler equipment is unavailable (24).

The study therefore has potential practical relevance for physiotherapy and exercise settings in Pakistan. A low-cost BFR protocol using commonly available equipment may provide an alternative means of delivering a substantial strengthening stimulus when access to dedicated commercial systems is limited. Nevertheless, affordability alone does not establish safety. Participant screening, individualized occlusion pressure, correct cuff application, symptom monitoring, and appropriate professional supervision remain essential components of BFR practice (21–24).

The non-significant Group × Time interactions require careful statistical interpretation. Conventional null-hypothesis significance testing evaluates whether available evidence is sufficient to reject a specified null hypothesis; failure to detect a statistically significant interaction does not establish that two interventions are equivalent. Formal equivalence or non-inferiority requires a prespecified clinically acceptable margin, appropriate sample-size planning for that margin, and an inferential procedure designed specifically to evaluate whether the treatment difference lies within that margin. The current trial was designed as a comparative parallel-group RCT rather than as a formal non-inferiority trial. Its findings therefore indicate that no statistically significant difference in longitudinal response was detected for the reported interaction analyses.

This distinction is especially important because the trial included 42 participants in the final per-protocol analysis. While the sample was sufficient to demonstrate substantial within-group changes, smaller between-group differences may be more difficult to detect. Non-significant interactions may consequently reflect genuinely similar responses, insufficient statistical precision for small differences, or a combination of both. Larger studies with confidence intervals around between-group change differences and prospectively defined equivalence or non-inferiority margins would permit stronger conclusions regarding comparative efficacy.

The trial had several methodological strengths. Participants were randomly allocated after baseline assessment, allocation concealment used sealed envelopes, both interventions were delivered according to standardized repetition and rest structures, BFR pressure was individualized relative to limb occlusion pressure, and outcomes were measured longitudinally at baseline, post-intervention, and four-week follow-up. Multiple wrist-strength directions were assessed rather than restricting evaluation to a single movement. Standardized participant positioning, repeated measurement procedures, anthropometric landmarks, and data-validation procedures further strengthened measurement consistency.

Several limitations should also be considered. First, the sample consisted exclusively of healthy young male university students, which limits generalizability to women, older adults, elite athletes, sedentary individuals, or patients with musculoskeletal and neurological disorders. The physiological and perceptual response to BFR may vary substantially across these populations. Future trials should therefore evaluate broader demographic and clinical groups.

Second, the active training period was limited to eight weeks and the post-training observation period to four weeks. This interval is sufficient to identify short-term strength adaptation but does not establish the durability of the response over several months. Longer follow-up would be necessary to determine whether BFRT and HIRT differ in maintenance of strength, training adherence, or longer-term structural adaptations.

Third, forearm circumference was measured anthropometrically. Although a standardized landmark and tension-regulated tape improve repeatability, circumference cannot distinguish contractile tissue from subcutaneous tissue or transient fluid-related changes. Future studies incorporating ultrasound or magnetic resonance imaging could directly quantify muscle thickness and cross-sectional area and thereby provide a stronger basis for conclusions regarding hypertrophy.

Fourth, the two training conditions differed not only in load and presence of vascular restriction but also in repetition volume and inter-set recovery. BFRT involved 75 repetitions with short 30-second rest periods, whereas HIRT involved 30 repetitions with 120-second rests. These differences are intrinsic to commonly used BFR and high-load resistance approaches but mean that the study compared complete training protocols rather than isolating the independent effect of cuff restriction.

Fifth, BFR can produce localized discomfort and altered perceptual responses. Although perceived exertion and adverse symptoms were monitored during the protocol, these variables were not analysed as primary comparative outcomes. Future studies should examine discomfort, perceived exertion, adherence, and participant preference alongside strength outcomes because tolerability may influence the feasibility of repeated BFR training.

Finally, the study did not evaluate tendon stiffness, bone mineral density, or other connective-tissue adaptations. High mechanical loading provides a distinct mechanical stimulus to muscle-tendon and skeletal tissues, and similar short-term muscular-strength outcomes should not be assumed to imply identical adaptation of tendon or bone. Longer-term studies incorporating musculoskeletal imaging and biomechanical outcomes would help clarify the relative strengths of BFRT and HIRT across different tissue systems.

Overall, the findings demonstrate that low-load BFRT can produce substantial wrist and grip-strength improvements in healthy young men despite the use of substantially lighter external resistance. High-intensity resistance training produced similarly substantial improvements, and the available interaction analyses did not identify statistically significant differences in longitudinal response for grip strength, wrist flexion, or wrist extension. The principal clinical and practical significance of BFRT is therefore not demonstrated superiority over HIRT but its ability to generate a meaningful strengthening stimulus at substantially lower external loads. This characteristic supports continued investigation of carefully prescribed BFRT in populations or settings where reducing mechanical loading is desirable.

CONCLUSION

Eight weeks of low-load blood flow restriction training at 20–30% of estimated 1RM and 50% of individual limb occlusion pressure produced substantial improvements in grip strength and multidirectional wrist strength in healthy male university students, with improvements largely maintained at four-week follow-up. High-intensity resistance training also produced substantial improvements, and the reported Group × Time analyses did not detect statistically significant differences in the longitudinal response of grip strength, wrist flexion, or wrist extension. Both approaches therefore supported strength development in this population, while the substantially lower external load required during BFRT supports its further investigation as a lower-load resistance-training strategy. The findings do not establish formal equivalence or non-inferiority between BFRT and HIRT.

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