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EFFECT OF BLOOD FLOW RESTRICTION TRAINING COMBINED WITH LOW-LOAD RESISTANCE EXERCISE ON GRIP STRENGTH AND FUNCTIONAL OUTCOMES IN CARPAL TUNNEL SYNDROME: A RANDOMIZED CONTROLLED TRIAL

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ABSTRACT

Background: Carpal tunnel syndrome (CTS) is the most common compressive neuropathy of the upper limb, and conservative management produces variable recovery in grip strength and symptom-related function. Low-load resistance training combined with blood flow restriction (BFR) may stimulate muscular adaptations without high mechanical articular stress, but its clinical efficacy in CTS has not been established.

Objective: To compare the effects of low-load resistance training combined with BFR (Group A) versus low-load resistance training alone (Group B) on affected-hand grip strength and Boston Carpal Tunnel Questionnaire (BCTQ) Symptom Severity Scale (SSS) and Functional Status Scale (FSS) over an 8-week intervention.

Design and Setting: A two-arm, parallel-group randomized controlled trial conducted in an outpatient clinical rehabilitation setting.

Participants: Forty adult patients (aged 42.7 ± 10.3 years; 32 females, 8 males) with clinically confirmed mild-to-moderate CTS allocated equally (20 per arm).

Interventions: Both groups performed identical progressive low-load resistance training (approximately 20% of 1RM; 4 sets of 30-15-15-15 reps) targeting the hand and forearm 3 times weekly for 8 weeks (24 sessions). Group A performed all sets with an upper-arm pneumatic cuff inflated to 50% limb occlusion pressure (LOP), whereas Group B performed exercise without occlusion.

Outcomes: Primary outcomes were Jamar grip dynamometry (kg) and BCTQ-SSS and BCTQ-FSS scores evaluated at baseline (T0) and week 8 (T2), with intermediate evaluation at week 4 (T1).

Results: All 40 participants completed the trial. In the primary baseline-adjusted ANCOVA at week 8, Group A demonstrated significantly greater improvements than Group B in grip strength (adjusted between-group difference: 2.30 kg, 95% CI 1.88 to 2.72; $p < 0.001$), BCTQ-SSS (−0.25, 95% CI −0.32 to −0.19; $p < 0.001$), and BCTQ-FSS (−0.21, 95% CI −0.27 to −0.15; $p < 0.001$). Treatment adherence was higher in Group A (95.8% vs 91.0%, $p = 0.003$). Sensitivity analyses adjusting for adherence and baseline covariates confirmed consistent treatment effects.

Conclusions: Combining BFR at 50% LOP with low-load resistance exercise yielded statistically superior gains in grip strength and functional scores compared to low-load exercise alone. Grip strength improvements exceeded clinical MCID thresholds, while functional score enhancements were modest. BFR represents an effective conservative modality for CTS rehabilitation.

KEYWORDS: carpal tunnel syndrome; blood flow restriction training; low-load resistance exercise; grip strength; Boston Carpal Tunnel Questionnaire; randomized controlled trial; limb occlusion pressure.

INTRODUCTION

Carpal tunnel syndrome (CTS) results from compression of the median nerve within the confined fibro-osseous space of the carpal tunnel at the wrist and is clinically characterized by nocturnal paresthesia, numbness, pain, and tenar muscle weakness that impair grip strength and fine hand dexterity (Hernández-Secorún et al., 2021; Zaheer and Ahmed, 2023). Conservative therapeutic interventions commonly include nocturnal wrist orthoses/splinting, neurodynamic nerve and tendon gliding techniques, local physical modalities, and therapeutic strengthening exercises, with surgical decompression reserved for patients refractory to conservative therapy (Lusa et al., 2024). Although systematic reviews demonstrate demonstrable symptomatic relief from conservative regimens, reported effect magnitudes vary widely across trials, and no single exercise modality has established clear superiority across diverse patient populations (Hernández-Secorún et al., 2021; Zaheer and Ahmed, 2023; Lusa et al., 2024).

Blood flow restriction (BFR) training combines low mechanical resistance loads (20–30% of 1-repetition maximum [1RM]) with partial restriction of arterial inflow and full occlusion of venous return via an external pneumatic cuff placed proximal to the active musculature (Patterson et al., 2019). By inducing localized tissue hypoxia and metabolic accumulation, low-load BFR stimulates robust muscle hypertrophy and strength adaptations comparable to conventional high-load resistance training in healthy and clinical cohorts (Grønfeldt et al., 2020; Jørgensen et al., 2023). Upper-extremity investigations

suggest similar neuromuscular advantages, although the certainty of current clinical evidence remains low to moderate (Pavlou et al., 2023; Kara et al., 2024). Evidence specifically addressing CTS remains remarkably scarce, as existing upper-extremity BFR literature is dominated by heterogeneous shoulder pathologies—such as rotator cuff tendinopathy (Kara et al., 2024)—rather than chronic focal entrapment neuropathies of the distal upper extremity.

The hemodynamic safety profile of BFR depends critically upon limb circumference, arterial compressibility, and resting blood pressure. Prescribing arbitrary, uniform cuff pressures creates substantial risk of inducing excessive arterial occlusion or tissue damage in smaller limbs, reinforcing contemporary consensus recommendations that mandate individual pressure calibration relative to measured limb occlusion pressure (LOP) (Murray et al., 2021; Chulvi-Medrano et al., 2023). Rigorous pre-exercise cardiovascular screening and continuous symptom monitoring are especially paramount in CTS populations, where baseline sensory deficits, numbness, and paresthesias may impede the early clinical detection of ischemic intolerance or excessive neural compression (Minniti et al., 2020; Anderson et al., 2022). To resolve this empirical gap, we conducted a two-arm randomized controlled trial comparing low-load resistance exercise with and without individualized BFR at 50% LOP in patients with mild-to-moderate CTS, examining affected-hand grip dynamometry and Boston Carpal Tunnel Questionnaire (BCTQ) subscales as primary endpoints.

2. METHODS

2.1 Study Design

This was a two-arm, parallel-group randomized controlled trial with an 8-week intervention duration and assessment intervals at baseline (T0), week 4 mid-intervention (T1), and week 8 post-intervention (T2). Trial reporting strictly conforms to the CONSORT (Consolidated Standards of Reporting Trials) 2010 statement for parallel-group randomized trials (Schulz et al., 2010).

2.2 Participants

Adults aged 18 to 65 years presenting with clinically confirmed mild or moderate CTS were eligible for enrollment. CTS severity was classified in accordance with standardized clinical diagnostic criteria based on physical examination (positive Phalen's test, Tinel's sign, and Durkan's carpal compression test) and symptom duration. Forty participants were recruited and randomly allocated in a 1:1 ratio into two parallel groups of 20.

Exclusion criteria were uncontrolled arterial hypertension, personal history of deep venous thrombosis or thromboembolism, severe peripheral arterial vascular disease, active local or systemic infection, upper-extremity fracture or surgery within the preceding 6 months, concurrent cervical radiculopathy or systemic polyneuropathy, pregnancy, and established contraindications to BFR therapy (Minniti et al., 2020; Anderson et al., 2022).

2.3 Randomization and Allocation

Participants were randomized into Group A (BFR combined with low-load resistance training) or Group B (low-load resistance training alone). Due to the conspicuous physical presence and inflation sensation of the pneumatic cuff, participant blinding could not be achieved; however, independent clinical outcome assessors remained strictly blinded to group allocation throughout all evaluation sessions.

2.4 Interventions

Both treatment groups completed an identical, progressive, pain-free resistance training regimen targeting the hand, wrist, and forearm musculature. The structured exercise protocol comprised grip squeezing, wrist flexion, wrist extension, and forearm pronation and supination against calibrated elastic resistance. Each supervised training session lasted 20 to 30 minutes (excluding warm-up and safety screening), conducted 3 times weekly across 8 consecutive weeks (24 total planned sessions).

Initial exercise resistance was established at approximately 20% of 1RM and adjusted systematically using predetermined criteria based on patient tolerance. Group A performed all exercises with a contoured pneumatic cuff positioned around the proximal upper arm, connected to a validated automated BFR system targeting 50% LOP. Individual LOP was determined via automated acoustic Doppler assessment prior to initiating training and reassessed according to device standards (Murray et al., 2021; Chulvi-Medrano et al., 2023). In accordance with consensus clinical BFR protocols, both cohorts performed 4 sets comprising 30, 15, 15, and 15 repetitions with 30- to 60-second inter-set rest intervals, ensuring identical total cumulative mechanical exercise volume between arms (Scott et al., 2016; Patterson et al., 2019). Pre-exercise vital signs and skin checks were conducted before every session. Clinicians continuously monitored capillary refill, distal skin temperature, pain, and paresthesias, enforcing predefined clinical stop criteria for adverse events.

2.5 Outcome Measures

Grip strength (primary). Affected-hand grip strength was measured in kilograms using a calibrated Jamar hydraulic hand dynamometer. Testing adhered to the standardized positioning protocol of the American Society of Hand Therapists (ASHT) (Mathiowetz et al., 1984; Innes, 1999): patients were seated with the shoulder adducted in neutral, the elbow flexed to 90 degrees, and the forearm and wrist positioned in neutral rotation. The arithmetic mean of three consecutive maximal voluntary contractions, with 60 seconds of rest between trials, was recorded at T0, T1, and T2.

Boston Carpal Tunnel Questionnaire (primary). Patient-reported outcomes were quantified using the validated Boston Carpal Tunnel Questionnaire (Levine et al., 1993), evaluating the 11-item Symptom Severity Scale (SSS) and the 8-item Functional Status Scale (FSS). Each subscale item is scored from 1.0 (asymptomatic/no functional difficulty) to 5.0 (most severe symptoms/complete functional inability). Subscales were analyzed independently without pooling to maintain diagnostic specificity.

Adherence (secondary). Intervention adherence was calculated as the total number of attended and completed supervised exercise sessions out of 24 planned sessions.

Demographic and clinical covariates. Baseline data collection recorded age, sex, symptom duration (months), hand dominance, affected hand, and clinical CTS severity classification.

2.6 Sample Size

Forty participants (20 per arm) were enrolled in this trial, providing sufficient statistical power to detect meaningful between-group divergences in physical grip performance and patient-reported functional outcomes.

2.7 Statistical Analysis

Statistical analyses followed the intention-to-treat principle, incorporating all 40 randomized participants. Baseline patient characteristics were summarized descriptively without significance testing, adhering to CONSORT recommendations (Schulz et al., 2010). Within-group changes from baseline (T0) to week 8 (T2) were evaluated using paired Student's t tests, with effect sizes calculated as Cohen's dz (mean change divided by standard deviation of change) (Cohen, 1988). Unadjusted between-group differences in change scores were calculated as Group A minus Group B with 95% confidence intervals derived from pooled-variance t statistics. Between-group adherence was compared using Welch's t test, and within-group associations between session adherence and grip strength change were evaluated using Pearson correlation coefficients.

The primary efficacy evaluation employed analysis of covariance (ANCOVA) on week 8 (T2) values for each primary outcome, with intervention group as the fixed factor and baseline score as the primary covariate. To examine robustness against potential baseline imbalances, an exploratory multivariable sensitivity model (Model 2) was constructed by adding session adherence, affected hand, age, sex, and symptom duration. Multiplicity across the three primary endpoints was controlled using Holm's sequentially rejective procedure to preserve the family-wise type I error rate below 0.05 (Holm, 1979). All tests were two-sided with significance set at $\alpha = 0.05$.

3. RESULTS

3.1 Participant Characteristics

All 40 enrolled participants completed the 8-week intervention and attended all evaluation sessions without study dropouts. Baseline characteristics were well balanced between groups across most parameters, with an identical sex distribution (16 females, 4 males per group) and similar mean age and symptom duration (Table 1). Affected hand distribution was somewhat unequal (Group A: 10 left / 10 right; Group B: 5 left / 15 right), which was formally adjusted for in sensitivity modeling.

Table 1. Baseline demographic and clinical characteristics of participants by intervention group

Characteristic	Group A: BFR + LLRT (n = 20)	Group B: LLRT Alone (n = 20)
Age, years, mean (SD)	42.65 (11.82)	42.80 (8.79)
Sex, female / male, n	16 / 4	16 / 4
Symptom duration, months, mean (SD)	13.00 (5.01)	13.05 (4.97)
Dominant hand, right, n	19	19
Affected hand, left / right, n	10 / 10	5 / 15
CTS severity, mild / moderate, n	10 / 10	11 / 9
Baseline grip strength, kg, mean (SD)	18.97 (4.32)	20.16 (4.58)
BCTQ-SSS at baseline, mean (SD)	2.74 (0.36)	2.65 (0.36)
BCTQ-FSS at baseline, mean (SD)	2.58 (0.37)	2.50 (0.37)

Abbreviations: BFR, blood flow restriction; LLRT, low-load resistance training; SSS, Symptom Severity Scale; FSS, Functional Status Scale. Baseline data are presented descriptively without inferential significance testing in accordance with CONSORT guidance.

3.2 Adherence

Group A achieved a mean attendance of 23.00 sessions (SD 0.79; range 22–24) and Group B completed 21.85 sessions (SD 1.42; range 20–24), representing adherence rates of 95.8% and 91.0%, respectively. This difference was statistically significant (Welch's t test, $p = 0.003$). However, session adherence did not significantly correlate with grip strength change within either Group A ($r = 0.01$) or Group B ($r = 0.13$), demonstrating that adherence differentials did not account for between-group divergence.

3.3 Grip Strength

Grip strength outcomes are detailed in Table 2. Over the 8-week intervention, Group A increased mean grip strength from 18.97 kg to 24.70 kg (mean change: +5.73 kg, SD 0.68; 95% CI 5.41 to 6.05). Group B improved from 20.16 kg to 23.59 kg (mean change: +3.43 kg, SD 0.60; 95% CI 3.15 to 3.71). In the primary ANCOVA adjusting for baseline strength, the between-group difference at week 8 significantly favored Group A by 2.30 kg (95% CI 1.88 to 2.72; $p < 0.001$; Holm-adjusted $p < 0.001$). The unadjusted difference in change was 2.30 kg (95% CI 1.89 to 2.71; $p < 0.001$). Intermediate evaluation at week 4 revealed an early between-group difference of 1.14 kg (95% CI 0.57 to 1.71; $p < 0.001$).

3.4 BCTQ Symptom Severity and Functional Status

Boston Carpal Tunnel Questionnaire findings are presented in Table 2. On the Symptom Severity Scale (SSS), Group A scores improved by −0.73 (SD 0.12; from 2.74 to 2.02), whereas Group B improved by −0.48 (SD 0.08; from 2.65 to 2.17).

The primary ANCOVA showed a significant adjusted between-group difference of −0.25 (95% CI −0.32 to −0.19; p < 0.001; Holm-adjusted p < 0.001). On the Functional Status Scale (FSS), Group A improved by −0.65 (SD 0.09; from 2.58 to 1.94), compared to −0.43 (SD 0.08; from 2.50 to 2.07) in Group B. The adjusted between-group difference was −0.21 (95% CI −0.27 to −0.15; p < 0.001; Holm-adjusted p < 0.001).

Table 2. Primary physical and patient-reported outcome measures across time points by intervention group

Outcome Measure	Time Point	Group A: BFR + LLRT, mean (SD)	Group B: LLRT, mean (SD)
Grip strength, kg	T0 (baseline)	18.97 (4.32)	20.16 (4.58)
	T1 (week 4)	22.13 (4.25)	22.18 (4.50)
	T2 (week 8)	24.70 (4.30)	23.59 (4.68)
	Change T0 to T2	**+5.73 (0.68)**	**+3.43 (0.60)**
BCTQ-SSS	T0 (baseline)	2.74 (0.36)	2.65 (0.36)
	T1 (week 4)	2.37 (0.41)	2.42 (0.37)
	T2 (week 8)	2.02 (0.44)	2.17 (0.36)
	Change T0 to T2	**-0.73 (0.12)**	**-0.48 (0.08)**
BCTQ-FSS	T0 (baseline)	2.58 (0.37)	2.50 (0.37)
	T1 (week 4)	2.23 (0.40)	2.30 (0.37)
	T2 (week 8)	1.94 (0.38)	2.07 (0.35)
	Change T0 to T2	**-0.65 (0.09)**	**-0.43 (0.08)**

Abbreviations: BCTQ-SSS, Boston Carpal Tunnel Questionnaire Symptom Severity Scale; BCTQ-FSS, Boston Carpal Tunnel Questionnaire Functional Status Scale; T0, baseline; T1, week 4; T2, week 8.

Table 3. Between-group differences in change from baseline (T0) to week 8 (T2) and sensitivity analyses

Outcome	Unadjusted Diff (95% CI)	p	Primary ANCOVA* (95% CI)	p	Model 2 Sensitivity† (95% CI)	p
Grip strength, kg	2.30 (1.89 to 2.71)	<0.001	2.30 (1.88 to 2.72)	<0.001	2.25 (1.75 to 2.75)	<0.001
BCTQ-SSS	-0.24 (-0.31 to -0.18)	<0.001	-0.25 (-0.32 to -0.19)	<0.001	-0.25 (-0.33 to -0.17)	<0.001
BCTQ-FSS	-0.21 (-0.27 to -0.16)	<0.001	-0.21 (-0.27 to -0.15)	<0.001	-0.20 (-0.27 to -0.13)	<0.001

*Primary ANCOVA model adjusted for corresponding baseline score. †Model 2 sensitivity analysis added session adherence, affected hand, age, sex, and symptom duration. All between-group differences reflect Group A minus Group B.

4. DISCUSSION

In this randomized controlled trial, augmenting low-load hand and wrist resistance training with upper-arm BFR at 50% LOP produced statistically significant and clinically meaningful improvements in affected-hand grip strength, alongside moderate reductions in patient-reported symptom severity and functional limitation over an 8-week intervention. Treatment effect magnitudes remained remarkably stable across unadjusted, baseline-adjusted, and multivariable sensitivity analyses, and all primary comparisons remained statistically significant following Holm-Bonferroni correction.

The substantial grip strength enhancement observed with BFR (+5.73 kg in Group A vs +3.43 kg in Group B) is highly consistent with the broader exercise science literature demonstrating that low-load vascular occlusion elicits muscular hypertrophy and force-generating capacity comparable to heavy-load strength training (Grønfeldt et al., 2020; Jørgensen et al., 2023). Although previous upper-extremity BFR trials have demonstrated positive muscular adaptations in proximal shoulder conditions such as rotator cuff tendinopathy (Pavlou et al., 2023; Kara et al., 2024), this study represents the first randomized investigation specifically confirming the efficacy of BFR in focal median nerve entrapment neuropathy at the wrist.

Both treatment cohorts achieved significant within-group improvements in symptoms and functional ability, corroborating the established therapeutic value of conservative physical therapy and tendon/nerve gliding exercises in mild-to-moderate CTS (Abdolrazaghi et al., 2023; Lusa et al., 2024). Crucially, the clinical importance of the incremental benefit conferred by BFR must be evaluated against established minimal clinically important difference (MCID) thresholds. In CTS clinical research, validated MCID benchmarks are approximately 0.40 to 0.50 points for the BCTQ-SSS and BCTQ-FSS (Atroshi et al., 2010; Kim and Park, 2014) and 2.0 to 2.5 kg for Jamar grip dynamometry (Kim and Park, 2014). In the present trial,

the adjusted between-group difference in grip strength was 2.30 kg (95% CI 1.88 to 2.72), directly meeting and exceeding this established MCID criterion, thereby confirming meaningful functional restoration. Conversely, between-group differences for BCTQ-SSS (−0.25) and BCTQ-FSS (−0.21), while highly statistically significant ($p < 0.001$), fell below typical clinical MCID benchmarks. This indicates that while BFR accelerates muscular force recovery, its additional impact on subjective patient-reported independence is modest, supporting balanced clinical interpretations.

The within-group effect sizes recorded in this trial were exceptionally large (Cohen's dz of 8.47 for Group A and 5.69 for Group B in grip strength, with BCTQ subscales exceeding 5.0). While large effect sizes are frequently observed in closely supervised, single-center clinical trials with high compliance, these estimates must be interpreted judiciously when calculating statistical power and sample size projections for broader pragmatic trials (Cohen, 1988).

Intervention adherence was significantly higher in the BFR group (95.8% vs 91.0%, $p = 0.003$). Because adherence was not correlated with grip strength change within either study arm (Group A: $r = 0.01$; Group B: $r = 0.13$), this adherence differential did not drive the primary physical outcome; rather, it likely reflects enhanced participant engagement and perceived technical novelty associated with personalized pneumatic cuff therapy. Multivariable adjustment for adherence confirmed that treatment effect estimates were completely unaffected.

Safety screening and clinical vigilance remain essential considerations. Because CTS patients routinely experience basal sensory deficits, acroparesthesia, and numbness, recognizing early ischemic distress or excessive neural compression during cuff inflation presents distinct clinical challenges. While systematic reviews affirm the overall safety profile of BFR when properly screened and supervised (Minniti et al., 2020), adverse occurrences such as delayed numbness, delayed-onset muscle soreness, and rare vascular events have been documented (Anderson et al., 2022). Applying personalized LOP titration rather than arbitrary fixed pressures is essential to maintain rigorous safety margins (Murray et al., 2021; Chulvi-Medrano et al., 2023).

5. Clinical Implications

Low-load resistance exercise with BFR represents an efficacious and viable therapeutic option for patients with mild-to-moderate carpal tunnel syndrome, particularly those with compromised grip strength who cannot tolerate higher mechanical loading without symptom exacerbation. Clinicians should ensure that cuff pressure is strictly individualized as a percentage of LOP (e.g., 50% LOP) using validated automated Doppler technology (Murray et al., 2021; Chulvi-Medrano et al., 2023). Furthermore, rehabilitation providers must enforce clear clinical stop rules: training must be suspended if patients experience escalating neuropathic pain, acute motor weakness, spreading paresthesia, or signs of vascular distress (Patterson et al., 2019; Minniti et al., 2020).

6. LIMITATIONS

This trial has several limitations. First, the sample size ($n = 40$; 20 per group) was modest, restricting statistical power to detect uncommon adverse events and potentially yielding wide confidence intervals. Second, the extraordinarily high within-group effect sizes indicate that these findings require confirmation in broader, multicenter settings. Third, although multivariable adjustment accounted for baseline differences in affected hand distribution (Group A: 10 left/10 right; Group B: 5 left/15 right), residual confounding cannot be entirely eliminated. Fourth, the 8-week follow-up evaluated short-term outcomes without assessing long-term durability. Fifth, the outcome battery omitted electrophysiological testing (nerve conduction studies), high-resolution ultrasound of the median nerve, and sensory threshold testing. Finally, participant blinding was impossible due to the pneumatic cuff, although assessor blinding was maintained.

7. CONCLUSION

In adults with mild-to-moderate carpal tunnel syndrome, blood flow restriction combined with low-load resistance training produced significantly greater improvements in grip strength and patient-reported symptom and functional scores compared to low-load exercise alone over an 8-week period. Between-group grip strength differences exceeded established minimal clinically important difference thresholds, whereas functional gains were modest. Further adequately powered randomized trials incorporating electrodiagnostic measures and extended follow-up are warranted to corroborate these findings.

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