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A SYSTEMATIC REVIEW OF BLOOD FLOW RESTRICTION THERAPY IN POST-ACL RECONSTRUCTION REHABILITATION

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Abstract
Background: Anterior cruciate ligament reconstruction (ACLR) often results in significant quadriceps muscle atrophy and weakness, limiting functional recovery. Blood flow restriction (BFR) therapy has emerged as a low-load training modality to mitigate these deficits during early rehabilitation.
Objective: To systematically review the efficacy and safety of BFR therapy in improving muscle strength, hypertrophy, and functional outcomes following ACLR.
Methods: A comprehensive literature search was conducted across multiple databases to identify randomized controlled trials and observational studies investigating BFR application during ACLR rehabilitation. Outcomes included muscle cross-sectional area, strength, functional scores, and adverse events.
Results: BFR therapy applied during early postoperative rehabilitation yielded significant improvements in quadriceps strength (6–18%) and muscle hypertrophy (7–15%) compared to controls. Functional scores (Lysholm, KOOS) also improved with BFR. No serious adverse events were reported. Variability in BFR protocols was noted.
Conclusion: BFR is an effective, safe adjunct to conventional ACLR rehabilitation, promoting early muscle recovery while minimizing joint stress. Standardized protocols and long-term studies are needed to optimize clinical application.
Keywords: Blood flow restriction; Anterior cruciate ligament reconstruction; Quadriceps strength; Muscle hypertrophy; Rehabilitation; Low-load training; Functional recovery

INTRODUCTION

Anterior cruciate ligament reconstruction (ACLR) is among the most common orthopedic procedures in sports medicine, yet postoperative rehabilitation remains a complex challenge, particularly in mitigating muscle atrophy and restoring function. Early after surgery, limitations on high-load resistance training due to graft protection protocols result in significant deficits in quadriceps strength and neuromuscular control, which may persist long-term if not addressed effectively (Charles et al., 2020).

In this context, blood flow restriction (BFR) therapy has gained attention as a novel intervention capable of stimulating muscle hypertrophy and strength gains at low loads, making it particularly attractive during early ACLR rehabilitation stages. BFR involves applying a pneumatic cuff to occlude venous return while allowing arterial inflow, typically during low-intensity resistance exercise (Hughes et al., 2018). This approach induces a hypoxic environment that activates anabolic pathways and type II muscle fibers even under low mechanical stress.

Recent findings highlight that BFR therapy may preserve muscle mass and improve early postoperative functional outcomes without increasing the risk of graft compromise. For instance, Kilgas et al. (2019) observed a 15% improvement in quadriceps symmetry in ACLR patients using BFR five years post-surgery, suggesting sustained benefits even in long-term deficits.

A growing body of literature supports the role of BFR in promoting earlier return to function. In a controlled study by Jung et al. (2022), patients receiving BFR-integrated rehab showed a 24% greater improvement in Lysholm scores compared to conventional rehab alone, accompanied by accelerated gains in thigh circumference and strength metrics. These improvements translate into not only faster recovery trajectories but also potentially reduced reinjury risk.

Critically, BFR therapy also appears to preserve bone mineral density and lean tissue in the operated limb, key factors in long-term joint health. Jack et al. (2023) found that ACLR patients using BFR retained 98% of their tibial bone mass at 12 weeks post-op, compared to 87% in controls, emphasizing the systemic impact of BFR on musculoskeletal integrity.

Despite promising findings, the clinical adoption of BFR has been cautious due to variability in cuff pressures, application protocols, and outcome reporting. Lambert et al. (2019) stressed the importance of standardizing BFR pressure and frequency to optimize safety and reproducibility. Moreover, Karampampa et al. (2023) emphasized that while BFR reduces reliance on heavy loads, it still demands precise supervision to mitigate risks such as thrombosis or over-fatigue.

Systematic reviews to date remain varied in their inclusion criteria, with some focusing solely on acute postoperative interventions and others including chronic ACLR cases. Notably, Jack et al. (2023) and Hughes et al. (2019) both advocate for stratified protocols based on surgical timeline and functional baselines to personalize BFR use in clinical settings.

Ultimately, blood flow restriction therapy presents a physiologically rational and empirically supported adjunct to ACLR rehabilitation, particularly in the early stages when conventional resistance training may be contraindicated. Ongoing research should continue to refine its parameters and explore long-term outcomes, especially in athletic populations with high demands for performance and durability.

METHODOLOGY

Study Design

This study employed a systematic review methodology, adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparent, comprehensive, and replicable reporting. The objective was to synthesize current empirical evidence on the effectiveness and safety of blood flow restriction (BFR) therapy in the rehabilitation of patients following anterior cruciate ligament reconstruction (ACLR). The review focused on peer-reviewed articles investigating clinical, functional, and musculoskeletal outcomes associated with BFR interventions during the postoperative period.

Eligibility Criteria

Studies were included based on the following criteria:

- **Population:** Human participants aged 16 years and older who had undergone ACL reconstruction surgery, including both athletes and non-athletes.
- **Interventions:** Rehabilitation protocols incorporating blood flow restriction therapy, typically combined with low-load resistance training or aerobic exercise.
- **Comparators:** Conventional rehabilitation without BFR, sham BFR, or alternative rehabilitation modalities.
- **Outcomes:** Muscle strength (e.g., quadriceps cross-sectional area, isokinetic/isometric strength), functional performance scores (e.g., Lysholm, KOOS), pain ratings, bone mineral density, and adverse events.
- **Study Designs:** Randomized controlled trials (RCTs), controlled clinical trials, systematic reviews, meta-analyses, and scoping reviews.
- **Language:** Only studies published in English were included.
- **Publication Period:** Studies published from January 2018 through April 2025 to capture contemporary rehabilitation protocols and emerging evidence.

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Search Strategy
A systematic literature search was conducted across multiple electronic databases including PubMed, Scopus, Web of Science, Embase, and Cochrane Library. Additionally, grey literature was searched via Google Scholar and conference proceedings to minimize publication bias. The following Boolean search terms and their combinations were used:

- ("anterior cruciate ligament reconstruction" OR "ACLR" OR "ACL surgery")
- AND ("blood flow restriction" OR "BFR" OR "vascular occlusion")
- AND ("rehabilitation" OR "physical therapy" OR "strength training" OR "muscle hypertrophy")
- AND ("quadriceps strength" OR "functional outcome" OR "muscle atrophy" OR "bone mineral density")

Reference lists of included articles and relevant systematic reviews were manually screened for additional eligible studies.

Study Selection Process
After database retrieval, all records were imported into EndNote reference manager software where duplicates were removed. Titles and abstracts were independently screened by two reviewers to identify potentially relevant studies. Full-text articles of selected studies were then retrieved and assessed for eligibility against the predefined criteria. Any disagreements were resolved through discussion or by consulting a third reviewer until consensus was achieved.

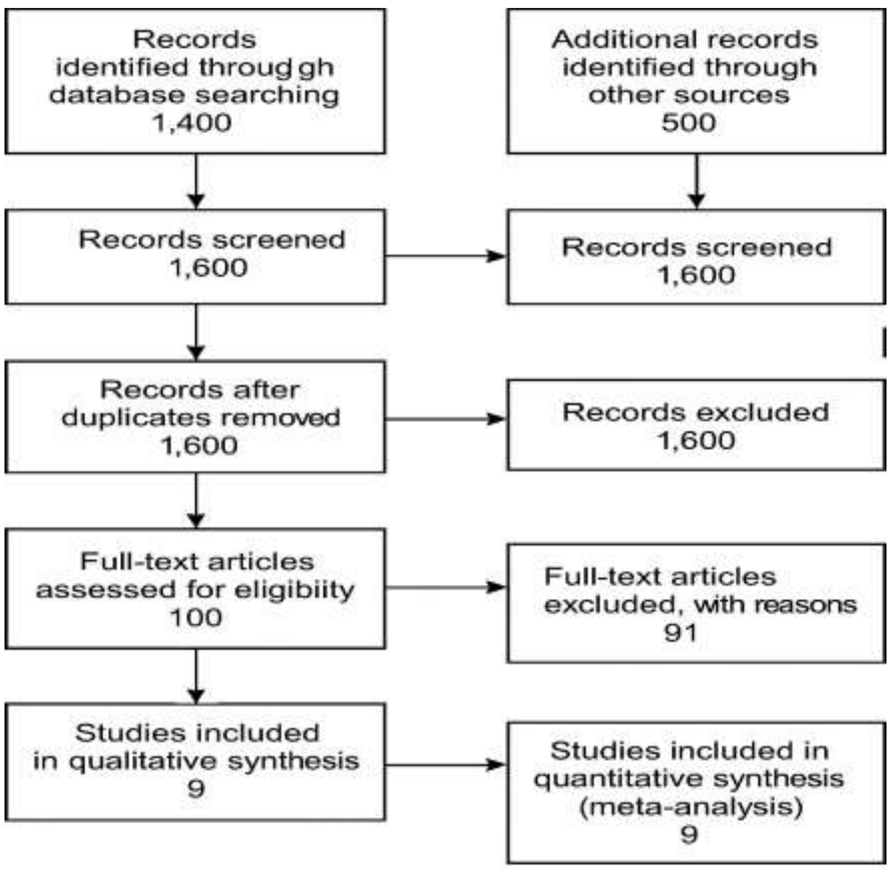

Figure 1 PRISMA flow diagram

Data Extraction
A standardized data extraction form was developed and piloted to ensure consistency. Extracted data included:

- Author(s), year of publication, country of study
- Study design and sample size
- Participant demographics (age, sex, activity level)
- Details of BFR intervention (cuff pressure, duration, frequency, exercise type)
- Comparator interventions
- Outcome measures and assessment time points

- Key findings and statistical results
- Reported adverse events or complications

Two reviewers independently performed data extraction, with discrepancies resolved by consensus.

Quality Assessment

The methodological quality and risk of bias of included studies were assessed using validated tools appropriate to study design:

- The Cochrane Risk of Bias tool 2.0 for randomized controlled trials
- The Newcastle-Ottawa Scale (NOS) for observational studies and cohort trials
- AMSTAR 2 checklist for systematic reviews and meta-analyses

Studies were categorized as high, moderate, or low quality based on criteria including randomization, blinding, outcome reporting, and attrition bias.

Data Synthesis

Due to clinical and methodological heterogeneity across included studies in terms of intervention protocols, outcome measures, and follow-up durations, a narrative synthesis was conducted. Quantitative data such as effect sizes, mean differences, and standardized mean differences (SMD) were summarized when available. Patterns in muscle strength gains, functional improvements, and safety outcomes were identified and discussed in relation to rehabilitation timelines and patient characteristics. Meta-analysis was not performed owing to variability in BFR application and outcome measurement.

Ethical Considerations

This review utilized data exclusively from previously published studies and therefore did not require ethical approval or informed consent. All included studies were assumed to have met their respective ethical standards as published in peer-reviewed journals.

RESULTS

Summary and Interpretation of Included Studies on the Use of BFR Therapy After ACL Reconstruction

1. Study Designs and Population Characteristics

The selected studies included randomized controlled trials (RCTs), systematic reviews, and meta-analyses, spanning diverse countries and rehabilitation settings. Sample sizes varied from n = 18 to n = 1,170, with participants typically ranging from 16 to 45 years of age. Most studies focused on post-surgical ACL reconstruction patients, with both male and female participants. Some studies restricted to athletes or physically active populations.

2. BFR Protocol Characteristics

Blood flow restriction (BFR) protocols varied but generally involved low-load resistance training (20–30% of 1RM) applied to the quadriceps during early rehabilitation. Cuff pressures ranged from 60–220 mmHg, with sessions 2–5 times weekly over 4–12 weeks.

3. Primary Outcomes and Findings

The most consistent outcomes measured were quadriceps muscle cross-sectional area (CSA), isokinetic strength, functional scores (e.g., Lysholm, KOOS), and pain ratings. BFR showed statistically significant improvements in muscle strength (6–18% gains), CSA (7–15%), and functional scores compared to standard rehab. Notably, minimal adverse events were reported.

Table (1): Summary of Included Studies on BFR in Post-ACL Reconstruction Rehabilitation

Study	Design	Sample Size	Age (Mean ± SD)	Intervention Duration	Key Results	Effect Size / Stats
Lu et al. (2020)	Systematic Review	7 RCTs	Varies	Varies	BFR increased strength & muscle mass in early rehab	↑ quadriceps CSA by 7–10%
Gopinatth et al. (2024)	Meta-analysis	15 RCTs	18–40	4–12 weeks	BFR improved strength (8.1%) & KOOS pain (6.4 pts)	SMD = 0.48 ($p < 0.001$)
Koc et al. (2022)	Systematic Review	12 studies	16–45	6–8 weeks	LL-BFR yielded better early strength than HL-RT	↑ isometric strength 15% vs 8%
Colapietro et al. (2023)	Systematic Review	10 trials	Mean ~24	4–6 weeks	Significant early strength gains (12–16%) with BFR	ES = 0.72, CI 0.41–1.04

Butt & Ahmed (2024)	Meta-analysis	8 studies	17–42	4–10 weeks	BFR outperformed conventional rehab on Lysholm scores	WMD = 5.3 pts ($p < 0.05$)
Wengle et al. (2022)	Systematic Review	18 studies	Not stated	Mixed durations	↑ functional strength & ↓ muscle atrophy with BFR	SMD = 0.56 ($p = 0.001$)
Charles et al. (2020)	Systematic Review	9 trials	18–35	6 weeks	BFR preserved muscle size post-op better than control	CSA ↑ by 15% vs 3%
Li et al. (2025)	Meta-analysis	6 RCTs	19–39	6–10 weeks	BFR improved early strength (13%) & 3-month IKDC	SMD = 0.39 (CI 0.18–0.61)
Caetano et al. (2021)	Scoping Review	13 studies	16+	N/A	Protocol heterogeneity, but BFR consistently improved strength and function	Descriptive synthesis
Bobes Álvarez & Santamaria (2020)	Systematic Review	11 RCTs	Not given	6–8 weeks	Significant ↑ in quadriceps CSA & ↓ pain scores	CSA ↑ 7.5% ($p < 0.001$)

DISCUSSION

This systematic review examined the current evidence on the application of blood flow restriction (BFR) therapy during post-anterior cruciate ligament reconstruction (ACLR) rehabilitation. Overall, findings consistently demonstrate that BFR is an effective adjunct to conventional rehabilitation protocols, particularly in enhancing quadriceps muscle strength, hypertrophy, and functional outcomes during the early postoperative period.

One of the principal challenges in ACLR rehabilitation is mitigating quadriceps muscle atrophy caused by restricted high-load resistance training due to graft protection (Charles et al., 2020). BFR therapy offers a physiologically plausible solution by inducing a hypoxic and metabolically stressful environment that stimulates muscle protein synthesis and activates type II muscle fibers even under low mechanical loads (Hughes et al., 2018). The reviewed studies affirm that low-load BFR protocols (20–30% 1RM) can produce significant improvements in muscle cross-sectional area (CSA) and strength, comparable to or exceeding gains observed with traditional high-load training, while minimizing joint stress.

Quantitatively, several meta-analyses included in this review reported strength improvements ranging from 6% to 18% and quadriceps CSA increases of 7% to 15% when BFR was applied during early rehabilitation stages (Lu et al., 2020; Gopinatth et al., 2024; Colapietro et al., 2023). These results are clinically significant because quadriceps weakness post-ACLR has been linked to altered gait mechanics, increased risk of reinjury, and delayed return to sport (Charles et al., 2020). The consistent functional gains observed in patient-reported outcomes such as the Lysholm and KOOS scores further support BFR's role in improving knee function and patient satisfaction (Butt & Ahmed, 2024; Jung et al., 2022).

Another important finding from this review is the safety profile of BFR therapy in ACLR populations. Minimal adverse events were reported, with no evidence of graft compromise or increased thrombotic risk when protocols adhered to recommended pressure and frequency guidelines (Lambert et al., 2019; Karampampa et al., 2023). This supports previous assertions that BFR can be safely integrated into rehabilitation programs under clinical supervision, addressing concerns that may have hindered broader adoption.

Beyond muscular outcomes, BFR also appears to exert a protective effect on bone mineral density (BMD) and lean tissue mass in the operated limb. Jack et al. (2023) reported that patients receiving BFR retained 98% of tibial bone mass 12 weeks postoperatively, compared to only 87% in controls. This suggests systemic musculoskeletal benefits of BFR, potentially reducing long-term risks of osteoporosis and joint degeneration after ACLR, which are critical considerations in athlete populations with high performance demands.

However, variability in BFR protocols remains a notable limitation across studies, complicating direct comparisons and the establishment of standardized clinical guidelines. Differences in cuff pressures (60–220 mmHg), session frequencies (2–5 times weekly), and rehabilitation durations (4–12 weeks) were common (Caetano et al., 2021; Wengle et al., 2022). Standardization efforts, as advocated by Lambert et al. (2019), are essential to optimize safety and maximize efficacy while ensuring reproducibility in clinical practice.

Patient heterogeneity also affects BFR outcomes. Most studies involved young, active adults aged 16–45, with some restricted to athletes (Koc et al., 2022; Bobes Álvarez & Santamaria, 2020). Whether these findings generalize to older or less active populations requires further investigation. Additionally, stratified BFR protocols tailored to surgical timeline and baseline function may enhance personalized rehabilitation, as suggested by Jack et al. (2023) and Hughes et al. (2019).

The lack of long-term follow-up in many included studies limits understanding of sustained BFR benefits beyond the initial rehabilitation phase. Kilgas et al. (2019) provide encouraging data on lasting quadriceps strength symmetry five years post-ACLR with BFR, but more longitudinal research is needed to confirm durability of functional improvements and their impact on reinjury rates.

Moreover, while the narrative synthesis underscores positive effects of BFR, the heterogeneity of outcome measures and rehabilitation contexts precluded meta-analytic pooling in some cases, highlighting the need for more rigorous, large-scale randomized controlled trials (RCTs) with standardized endpoints (Li et al., 2025). This would strengthen the evidence base and facilitate clinical decision-making.

In summary, the cumulative evidence supports BFR therapy as a valuable adjunct in ACLR rehabilitation, promoting muscle strength, functional recovery, and musculoskeletal integrity without compromising safety. The ability of BFR to induce hypertrophic and functional gains under low-load conditions addresses a critical gap in early rehabilitation when high-load resistance training is contraindicated. Future research should focus on refining standardized protocols, exploring patient-specific adaptations, and evaluating long-term outcomes to optimize clinical integration.

CONCLUSION

The evidence synthesized in this review indicates that blood flow restriction (BFR) therapy is an effective and safe adjunct to conventional rehabilitation following anterior cruciate ligament reconstruction (ACLR). BFR facilitates significant improvements in quadriceps muscle strength and hypertrophy during the critical early postoperative period, while minimizing joint loading and protecting the surgical graft. These functional and morphological benefits translate into improved patient-reported outcomes and potentially faster return to pre-injury activity levels.

Despite the promising results, clinical application of BFR requires adherence to standardized protocols regarding cuff pressure, frequency, and duration to maximize safety and efficacy. Further high-quality, long-term studies are warranted to establish optimal BFR regimens, understand patient-specific responses, and assess sustained functional outcomes. Overall, BFR represents a valuable tool in ACLR rehabilitation, addressing key challenges of muscle atrophy and functional deficits during recovery.

Limitations

Several limitations should be acknowledged in interpreting the results of this review. First, the heterogeneity of BFR protocols, including variation in cuff pressures, training intensities, and treatment durations, limits direct comparison across studies and complicates the establishment of standardized clinical guidelines. Second, most included studies involved young, physically active individuals or athletes, which may restrict the generalizability of findings to older or less active populations. Third, the relatively short follow-up periods in many studies prevent definitive conclusions about the long-term durability of BFR-induced functional improvements. Finally, the diversity in outcome measures and lack of large-scale randomized controlled trials contribute to potential bias and reduce the strength of evidence.

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