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Blood Flow Restriction Training in Postoperative Musculoskeletal Rehabilitation

Bartosz Rodziewicz

Medical University of Gdańsk, Marii Skłodowskiej-Curie 3a, 80-210 Gdańsk, Poland

ORCID: https://orcid.org/0009-0003-1925-9952

E-mail: b.rodziewicz@gumed.edu.pl

Mateusz Fidut

Medical University of Gdańsk, Marii Skłodowskiej-Curie 3a, 80-210 Gdańsk, Poland

ORCID: https://orcid.org/0009-0000-3323-2527

E-mail: m.fidut@gumed.edu.pl

Mikołaj Kacperski

Medical University of Gdańsk, Marii Skłodowskiej-Curie 3a, 80-210 Gdańsk, Poland

ORCID: https://orcid.org/0009-0004-5921-7324

E-mail: m.kacperski@gumed.edu.pl

Abstract

Background: Blood flow restriction (BFR) training applies partial vascular occlusion during low-load exercise, offering a clinically compelling adjunct in postoperative rehabilitation. It addresses the paradox of maintaining muscle mass when conventional high-load exercise is contraindicated.

Aim: To conduct a narrative review of BFR's mechanisms, efficacy, and safety in postoperative musculoskeletal disorders, emphasising ACL reconstruction, total knee arthroplasty (TKA), rotator cuff, and meniscal surgery.

Material and Methods: A systematic search of PubMed, Web of Science, and Scopus was performed for English, peer-reviewed human studies published between January 2005 and March 2026. Included studies employed defined BFR protocols for perioperative or postoperative musculoskeletal rehabilitation.

Results: Based on 29 studies, BFR significantly mitigates quadriceps atrophy and accelerates strength recovery post-ACL reconstruction compared to load-matched controls. Its efficacy extends to TKA, rotator cuff, and meniscal procedures. Mechanisms include metabolic stress, mTORC1 activation, hormonal upregulation, and regenerative intercellular mitochondrial transfer. BFR is safe when utilising individualised limb occlusion pressure (LOP) protocols. However, the current literature remains limited by significant protocol heterogeneity and a lack of human biopsy studies confirming these molecular mechanisms.

Conclusions: BFR enables load-compromised patients to achieve resistance training adaptations previously requiring high intensities. Standardising protocols and conducting multicentre trials are priorities for evidence-based integration.

Keywords: Blood flow restriction training; BFR; musculoskeletal rehabilitation; ACL reconstruction; total knee arthroplasty; rotator cuff repair; muscle atrophy; postoperative rehabilitation; occlusion training

1. Introduction

The management of skeletal muscle atrophy and functional decline following orthopaedic surgery remains one of the enduring challenges in postoperative rehabilitation medicine. Surgical interventions on load-bearing joints—such as anterior cruciate ligament (ACL) reconstruction, total knee arthroplasty (TKA), rotator cuff repair, and meniscal procedures—invariably necessitate periods of restricted weight-bearing and reduced mechanical loading. During this acute phase, pronounced muscle atrophy and strength deficits manifest rapidly; for instance, the cross-sectional area of the quadriceps femoris may diminish by as much as 15–25% within the first weeks following ACL reconstruction [1]. This catabolic trajectory is further compounded by arthrogenic muscle inhibition (AMI)—a neurally mediated reflex that restricts voluntary muscle activation and persists well beyond the initial tissue healing phase [2].

Counteracting this decline conventionally requires resistance training at intensities sufficient to induce hypertrophic adaptation, typically prescribed at 70–85% of a patient's one-repetition maximum (1RM) [3]. However, applying such mechanical loads is frequently contraindicated in the early postoperative period due to the risk of graft failure, wound complications, or implant malpositioning. Consequently, this therapeutic gap has historically been filled by low-load exercises. While clinically safe, these exercises generally provide an insufficient mechanical and metabolic stimulus to arrest progressive disuse atrophy.

Blood flow restriction (BFR) training—also known as occlusion training or KAATSU—has emerged as a mechanistically grounded intervention to resolve this clinical paradox [4]. Originally conceptualized in the 1960s by Yoshiaki Sato, BFR training involves applying a pneumatic cuff or tourniquet to the proximal limb to partially restrict venous outflow while maintaining arterial inflow during low-load resistance exercise (typically 20–40% 1RM) [5]. The ensuing haemodynamic and metabolic perturbations—including localized hypoxia, venous pooling, metabolite accumulation, and enhanced cellular stress signalling—trigger anabolic cascades normally reserved for high-intensity exertion [6]. This allows patients to achieve meaningful hypertrophic and strength adaptations at loads that impose minimal joint stress.

The evidence base supporting BFR in clinical rehabilitation has evolved significantly. Early foundational syntheses, such as the 2017 meta-analysis by Hughes et al., established the moderate-to-large effect of BFR on strength preservation compared to standard low-load training, particularly identifying ACL reconstruction and osteoarthritis populations as primary beneficiaries [7]. More recently, the scope of research has broadened considerably. Recent network meta-analyses position BFR among the most efficacious interventions for immediate postoperative recovery [8]. Furthermore, mechanistic science is advancing rapidly from descriptive metabolic models to the molecular level; contemporary murine investigations have even demonstrated that BFR stimulates directed intercellular transfer of mitochondria from fibro-adipogenic progenitor cells (FAPs) to myocytes—highlighting regenerative pathways that extend beyond the purely mechanical exercise stimulus [9].

Despite this rapidly expanding body of literature, the integration of BFR into standard care remains heterogeneous, with ongoing debate regarding optimal technical parameters, contraindications, and specific clinical applications. Therefore, this narrative review synthesises the current evidence concerning the physiological mechanisms, technical parameters, clinical efficacy across surgical populations, and safety considerations of BFR training. By critically appraising both established clinical outcomes and emerging molecular paradigms, this review aims to provide clinicians, surgeons, and rehabilitation scientists with a comprehensive resource to inform the evidence-based integration of BFR into postoperative musculoskeletal care pathways.

2. Literature Search Strategy and Inclusion Criteria

The literature search was conducted on 15 March 2026 across three major electronic databases: PubMed, Web of Science (Core Collection), and Scopus. Search strings combined the primary terms "blood flow restriction", "occlusion training", and "vascular occlusion exercise" with each of the following secondary terms: "rehabilitation", "postoperative", "anterior cruciate ligament", "ACL reconstruction", "total knee arthroplasty", "rotator cuff", "meniscal repair", "hip arthroplasty", "spinal surgery", "muscle atrophy", "prehabilitation", and "tendinopathy". Boolean operators (AND/OR) were applied to maximise search sensitivity. Additionally, the reference lists of identified systematic reviews and meta-analyses were manually screened to capture any relevant primary sources not retrieved in the initial search.

Inclusion criteria were defined as follows: (1) publication in a peer-reviewed English-language journal; (2) clinical studies involving human subjects, or foundational in vivo/in vitro models demonstrating direct translational relevance to perioperative musculoskeletal rehabilitation; (3) utilisation of a defined BFR training protocol applied at any stage of the perioperative continuum; (4) reporting of at least one quantifiable outcome measure, including but not limited to muscle cross-sectional area, maximal voluntary contraction, isokinetic peak torque, limb symmetry index, patient-reported outcome measures, or gait parameters; and (5) publication between January 2005 and March 2026.

Given the narrative scope of this review, a broad methodological spectrum was considered eligible, encompassing systematic reviews, meta-analyses, randomised controlled trials, prospective and retrospective cohort studies, controlled laboratory investigations, narrative reviews, case series, and expert commentaries. Conference abstracts, dissertations, non-peer-reviewed publications, and non-English manuscripts were excluded. Ultimately, 29 studies met the inclusion criteria and were included in this review.

3. Physiological and Molecular Mechanisms of Blood Flow Restriction Training

3.1 Haemodynamic Principles and Metabolic Stress

The fundamental haemodynamic objective of blood flow restriction (BFR) training is the selective occlusion of venous efflux from the working limb alongside the preservation of arterial perfusion. The application of a proximal cuff at an appropriately calibrated pressure—typically 40–80% of limb occlusion pressure (LOP)—induces venous pooling distal to the tourniquet. Consequently, this creates a hypoxic, metabolite-rich intramuscular milieu.

The rapid accumulation of inorganic phosphate, hydrogen ions, lactate, and adenosine stimulates type III and IV afferent nerve fibres (triggering the "metaboreflex"), thereby inducing a constellation of systemic physiological responses [1, 2]. Historically, this concentration of metabolic by-products has been conceptualised as the primary anabolic stimulus in BFR exercise, operating synergistically with the mechanical tension generated by low-load resistance training. Both pathways converge on the mammalian target of rapamycin complex 1 (mTORC1) signalling axis. This convergence effectively upregulates protein synthesis, attenuates proteolytic pathways (most notably the ubiquitin–proteasome system), and promotes myofibrillar accretion. The net outcome is a hypertrophic response disproportionate to the imposed mechanical loading, which remains the defining hallmark of BFR training [1, 3].

3.2 Hormonal and Anabolic Signalling Responses

In addition to intracellular mTOR activation, BFR training elicits a robust systemic hormonal response. Acute elevations in circulating growth hormone (GH) concentrations—frequently exceeding those observed during conventional high-load resistance exercise of equivalent duration—have been consistently documented following BFR interventions. Furthermore:

- insulin-like growth factor 1 (IGF 1) and its binding proteins are modulated in a manner congruent with anabolic cellular remodelling.
- testosterone and catecholamine responses, while somewhat variable, are significantly enhanced relative to matched low-load exercise performed without vascular occlusion [1, 4].

These systemic hormonal perturbations are hypothesised to mediate cross-education effects in the contralateral, unoccluded limb. This phenomenon holds considerable clinical relevance for patients in whom direct loading of the operative extremity is temporarily contraindicated. For instance, Sevinc et al. [5] demonstrated significant contralateral quadriceps strength preservation in post-anterior cruciate ligament reconstruction (ACLR) patients who underwent unilateral BFR exercise, an observation well-supported by the broader cross-education literature.

3.3 Neuromuscular Mechanisms and Arthrogenic Muscle Inhibition (AMI)

Arthrogenic muscle inhibition (AMI)—defined as the neurally mediated, reflexive inhibition of musculature surrounding an injured or surgically treated joint—constitutes a primary barrier to quadriceps recovery following knee surgery. AMI is predominantly driven by aberrant afferent signalling from joint mechanoreceptors and nociceptors to the spinal cord, resulting in depressed motor neuron excitability and diminished voluntary muscle activation [6, 10]. Conventional resistance training, limited to loads achievable in the early postoperative phase, is often insufficient to overcome the AMI threshold and restore complete neural drive.

Notably, BFR training appears to engage neuromuscular mechanisms distinct from conventional low-load exercise:

- Enhanced Motor Unit Recruitment: The metabolite-mediated activation of group III/IV muscle afferents prompts an augmented motor unit recruitment pattern. This facilitates the earlier and more comprehensive activation of higher-threshold type II motor units, which are otherwise disproportionately susceptible to disuse atrophy [1, 2].
- Bypassing AMI: This altered recruitment strategy may partially bypass or progressively reverse AMI. Electromyographic analyses reveal significantly greater motor unit activity during BFR exercise compared with non-occluded low-load exercise at identical relative intensities.

Further supporting this mechanism, Lauber et al. [11] demonstrated that even isometric BFR exercise acutely improves voluntary activation and neuromuscular efficiency metrics. This implies that the occlusive stimulus alone—independent of dynamic articulation—can recruit and fatigue fast-twitch muscle fibres. Such an effect provides a critical mechanistic advantage for early postoperative patients restricted from range-of-motion exercises.

3.4 Intercellular Mitochondrial Transfer: A Novel Mechanistic Frontier

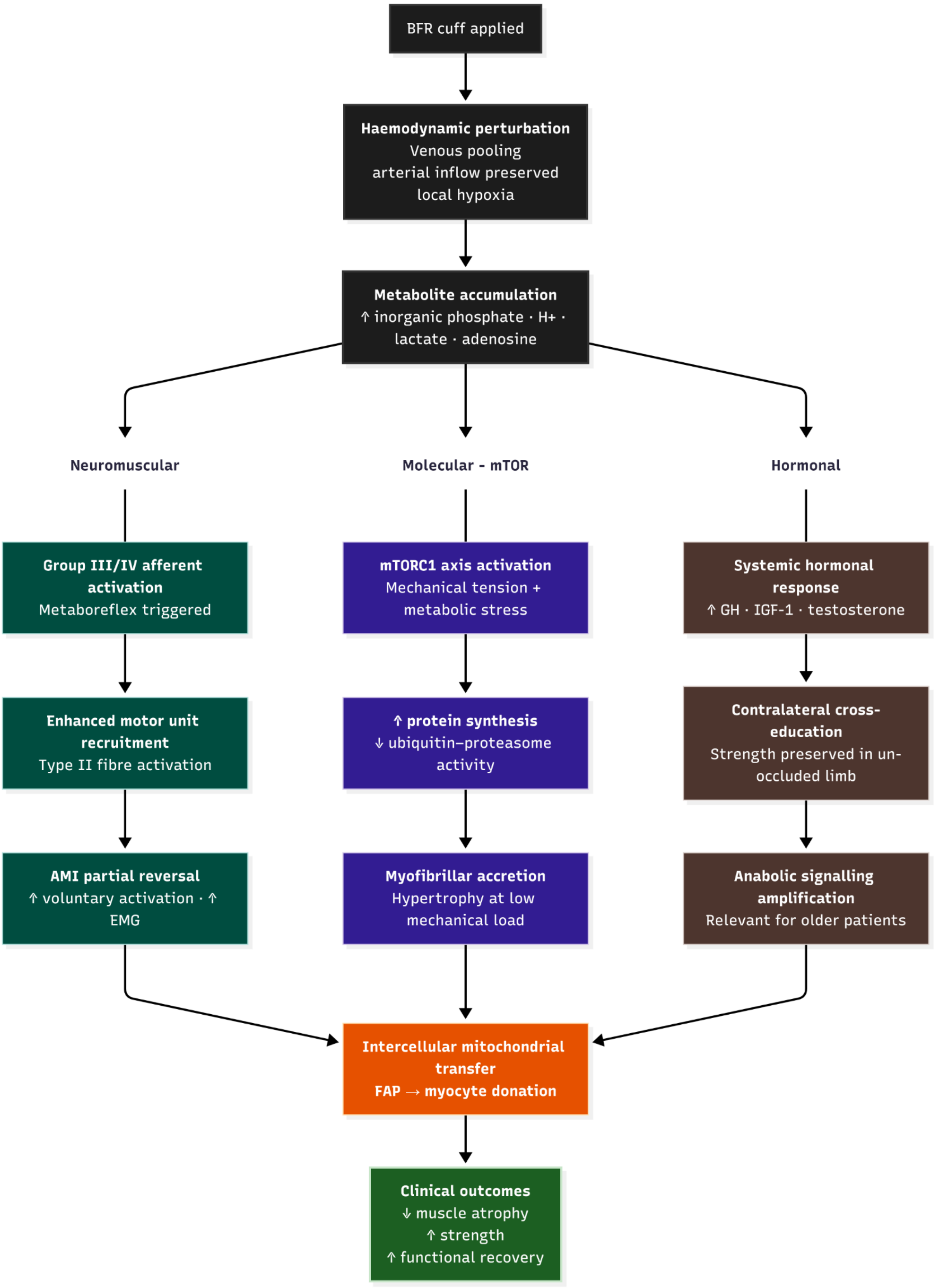
Perhaps the most mechanistically provocative recent discovery concerns BFR-induced intercellular mitochondrial transfer. In a rigorously controlled murine model published in 2026, Milan et al. [9] utilised Prrx1-Cre/MitoTag reporter mice to establish that BFR stimulates the directed transfer of mitochondria from fibro-adipogenic progenitor cells (FAPs)—intramuscular mesenchymal stromal cells canonically associated with fibrotic and fatty degeneration—to adjacent myocytes.

This phenomenon was detectable in the supraspinatus muscle within 24 hours of a single BFR session and persisted for up to three days. In a model simulating a massive rotator cuff tear (tendon transection combined with denervation), BFR treatment yielded profound regenerative outcomes at two and six weeks post-injury relative to untreated controls. Key findings included:

- Significantly enhanced mitochondrial transfer.
- Mitigated muscle atrophy.
- Attenuated fatty infiltration and reduced fibrotic progression.
- Improved forepaw weight-bearing symmetry.

Clinical Implications: These data expand the mechanistic framework of BFR beyond standard metabolic and neural adaptations, positioning it within the realm of regenerative biology. The clinical significance of FAP-mediated mitochondrial donation is highlighted by the near-universal occurrence of fatty infiltration in massive rotator cuff tears and chronic quadriceps atrophy following ligamentous trauma. Should BFR demonstrably shift human FAP biology from a degenerative to a regenerative phenotype, it would constitute a genuinely novel therapeutic modality with implications far exceeding conventional exercise physiology [9]. While these data currently originate from a murine model, they provide a compelling rationale for the application of BFR in human pathologies characterised by profound muscle degeneration, such as that observed following rotator cuff repair or prolonged immobilisation.

FIGURE 1



4. Technical Considerations and Clinical Application

4.1 Cuff Design and Application Principles

The optimal efficacy and safety of BFR are fundamentally dependent upon precise and reproducible cuff pressure delivery. Commercially available devices range from automated pneumatic systems (Delfi PTS, BI Medical Delphi, Owens Recovery Science Personalized Tourniquet System) to manually applied elastic wraps. Because manual wraps introduce substantial intra- and inter-session variability in occlusive pressure, contemporary evidence strongly advocates for automated, LOP-referenced devices in clinical practice to ensure patient safety and methodological consistency [12, 13].

Cuff morphometry and anatomical placement critically dictate the absolute occlusive pressure required:

- Cuff Width: Wider cuffs distribute force over a larger surface area, thereby achieving occlusion at lower absolute pressures. Standard practice dictates a 10–12 cm width for the lower extremity and a 5–7 cm width for the upper extremity.
- Cuff Placement: To maximise venous restriction at the lowest efficacious absolute pressure, cuffs must be positioned at the most proximal aspect of the limb (the proximal thigh for the lower extremity and the axillary region for the upper extremity) [2, 12].

4.2 LOP-Based Titration

Limb occlusion pressure (LOP) is defined as the minimum tourniquet pressure necessary to completely arrest arterial flow to the distal limb, as verified by Doppler ultrasound or distal pulse oximetry. Crucially, therapeutic BFR training is executed at sub-maximal pressures rather than full arterial occlusion. This individualised, relative pressure titration accounts for patient-specific variations in limb circumference, tissue composition, resting blood pressure, and cuff dimensions. Consequently, LOP-based protocols demonstrate superior safety profiles compared with fixed absolute-pressure methodologies [13–15].

Standard therapeutic pressure parameters include:

- Lower Extremity: Pressures corresponding to 40–60% LOP are predominately utilised in post-surgical cohorts, generally yielding absolute pressures between 80 and 160 mmHg, contingent upon patient anthropometrics.

- Upper Extremity: Protocols typically employ 40–50% LOP, generating absolute pressures ranging from 50 to 100 mmHg.

To standardise safe prescription, Nascimento et al. [13] introduced a clinical risk stratification framework that synthesises LOP-based pressure titration with individual patient comorbidity profiles.

4.3 Exercise Protocol Parameters

In musculoskeletal rehabilitation, standard BFR protocols consistently utilise low-intensity resistance, typically 20–40% of the patient's one-repetition maximum (1RM).

- The Canonical Repetition Scheme: Derived from foundational KAATSU protocols, this model prescribes four sets of 30, 15, 15, and 15 repetitions. A brief inter-set rest period of 30–60 seconds is maintained, during which cuff pressure remains inflated. This specific high-volume structure is engineered to maximise metabolite accumulation and subsequent fatigue-induced motor unit recruitment [2, 7].
- Post-Surgical Modifications: When dynamic loading is contraindicated in the immediate postoperative phase, BFR parameters require adaptation. Evidenced-based modifications include:
  - Isometric BFR: Induces intramuscular fatigue without requiring joint articulation.
  - NMES-BFR: The integration of neuromuscular electrical stimulation with BFR. Kong et al. [16] reported that combined NMES-BFR in early post-ACLR patients yielded significantly greater preservation of quadriceps cross-sectional area and voluntary activation compared with either modality in isolation.
  - Low-Velocity Walking: Cutisque et al. [17] established the feasibility of low-velocity walking with BFR during the early weeks post-ACLR, eliciting meaningful lower limb muscle activation and thereby expanding BFR's utility to functional, weight-bearing tasks.

4.4 Prehabilitation Paradigm

An increasingly recognised clinical application of BFR is its use in preoperative muscle optimisation—or prehabilitation—designed to elevate the patient's functional baseline prior to surgical intervention.

Franz et al. [18, 19] pioneered the conceptualisation of BFR-based prehabilitation for total knee arthroplasty (TKA) candidates, hypothesising that preoperative BFR could build sufficient muscular reserve to attenuate the inevitable postoperative functional decline. Recent prospective data corroborate this mechanistic rationale:

- Jorgensen et al. [20] demonstrated that a preoperative BFR regimen for TKA candidates yielded significantly greater postoperative quadriceps strength at six and twelve weeks relative to standard preoperative exercise.
- Advancing this continuum of care, Tian et al. [21] are currently directing a multicentre randomised controlled trial evaluating a combined protocol of preoperative BFR followed by postoperative continuation in ACLR patients. Primary endpoints include MRI-derived quadriceps cross-sectional area and limb symmetry indices at twelve months.

5. Blood Flow Restriction Training Following Anterior Cruciate Ligament Reconstruction

The postoperative management of quadriceps atrophy and subsequent strength deficits following ACLR constitutes the most thoroughly investigated application of BFR training in orthopaedics. This extensive research focus reflects both the sheer volume of procedures performed—approximately 120,000 primary ACLRs annually in the United States alone—and the profound, recalcitrant functional impairments that characteristically complicate recovery. Despite conventional rehabilitation, quadriceps deficits exceeding 20% compared to the uninjured limb are frequently documented at the time of return-to-sport clearance, a deficit mechanistically linked to elevated re-injury rates and compromised long-term joint function [6, 8, 10].

5.1 Evidence for Muscle Mass Preservation and Strength Recovery

The systematic evidence substantiating BFR efficacy following ACLR is both robust and rapidly expanding:

- Systematic Efficacy: In a scoping review encompassing 7 studies, Caetano et al. [22] concluded that BFR training consistently provided superior preservation of quadriceps cross-sectional area and accelerated strength recovery compared with matched non-occluded low-load exercise.

- Clinical Significance: A 2024 systematic review by Colombo et al. [23] comparing blood flow restriction (BFR) to standard ACL rehabilitation found highly conflicting evidence regarding its superiority in improving muscle strength and size. While BFR demonstrates potential benefits, the authors concluded that larger, standardised trials are required before it can definitively replace traditional rehabilitation methods.

A 2026 randomised controlled trial by Barzyk et al. [24] involving 30 patients investigated the addition of blood flow restriction (BFR) to early low-load strength training after ACL reconstruction. The authors found no significant differences between the BFR and control groups regarding pain reduction, maximum strength, or range of motion. They concluded that combining BFR with low-load training provides no additional clinical benefits over low-load training alone in the early postoperative phase. Taken together, the post-ACLR literature does not yet support BFR as a replacement for conventional rehabilitation, but it does support its use as a low-risk adjunct in patients in whom higher mechanical loads are contraindicated, with the strongest signal for preservation of quadriceps cross-sectional area and earlier strength recovery in the first weeks after surgery [22, 23, 25].

5.2 Perioperative and Early Postoperative BFR Protocols

The perioperative window—spanning late-stage prehabilitation through the immediate postoperative phase—is increasingly viewed as a critical period of therapeutic leverage for BFR implementation. Okoroha et al. [25] evaluated patients undergoing BFR training as part of a standardised 12-week postoperative protocol following ACL reconstruction. Although the BFR cohort exhibited significantly greater quadriceps strength and better functional scores at 6 weeks postoperatively, this early advantage dissipated over time. At 12 weeks (3 months), there were no significant differences in muscle strength or patient-reported outcomes (PROMs) between the BFR group and those receiving standard care. A 2020 systematic review by Lu et al.[26] indicates that while perioperative BFR shows potential for improving muscle strength and hypertrophy, current evidence is sparse and heterogeneous. The authors emphasise that larger, standardised trials are required before drawing definitive conclusions about its efficacy across the operative continuum.

5.3 Mid- and Late-Phase Rehabilitation and Home-Based BFR

The clinical utility of BFR extends beyond early acute atrophy mitigation, offering solutions for persistent deficits. For instance, a study by Kilgas et al. [27] demonstrated the effectiveness of a home-based BFR exercise program for patients experiencing chronic quadriceps weakness several years post-ACLR. Following the intervention, knee extensor strength symmetry significantly increased from 88% to 99%, matching uninjured controls. This highlights that home-based, technology-assisted BFR is not only feasible and safe but also highly effective for long-term recovery, helping to overcome geographical or resource barriers in physical therapy.

5.4 Hamstring Function

While the extensor mechanism is the primary focus of ACL rehabilitation, BFR is also utilised for hamstring recovery, especially when the hamstring is used as a graft donor site. A 2023 case report by Ceccarelli et al. [28] documented the rehabilitation of a professional footballer following ACL reconstruction. Implementing a low-load BFR protocol targeting the ischiocrural muscles, starting at six weeks post-surgery, resulted in an almost 60% increase in hamstring strength over a four-week period. This suggests BFR's potential to safely accelerate strength recovery in graft donor sites without requiring heavy mechanical loads.

6. Blood Flow Restriction Training in Total Knee Arthroplasty (TKA)

Postoperative muscle weakness is a profound complication following Total Knee Arthroplasty (TKA), with quadriceps strength losses reaching up to 62% in the first postoperative month, severely limiting functional independence. Traditional high-load resistance training is often impossible in this demographic due to joint pain, swelling, and surgical precautions. Recent systematic reviews, such as the 2025 review by Tiss et al. [29], confirm that low-load BFR is a safe and effective adjunct for this population. Current evidence indicates that incorporating BFR—both as prehabilitation and postoperative therapy—significantly improves early functional outcomes (30-second sit-to-stand and walking tests) and attenuates the loss of muscle mass, without increasing the risk of adverse cardiovascular or wound-healing events. Key Clinical Findings and Safety Guidelines for BFR Training are shown in Table 1.

Table 1.

Category / Condition	Risks	Clinical Action	Reference
Efficacy: ACL Reconstruction	Conflicting evidence: potential benefit in quadriceps CSA preservation and strength recovery; some RCTs show no added value over low-load exercise alone.	Use as adjunct to standard rehab; larger standardised trials needed before replacing conventional therapy.	Caetano et al. (2021) [22] Colombo et al. (2024) [23]; Zhao et al. (2026) [8]
Efficacy: Total Knee Arthroplasty (TKA)	Attenuates muscle mass loss; improves early functional outcomes (sit-to-stand, walking); no increase in adverse events.	Safe pre- and postoperatively; adapt intensity to patient's pain tolerance.	Tiss et al. (2025) [29]; Jørgensen et al. (2024) [20]
Absolute Contraindication	Active deep vein thrombosis (DVT) or pulmonary embolism (active or within 3 months).	Prohibited – risk of thrombus propagation or embolism.	Anderson et al. (2022) [14]; Cristina-Oliveira et al. (2020)[15]
Absolute Contraindication	Severe peripheral arterial disease (ABI < 0.5) or acute limb ischemia.	Prohibited – risk of ischemic necrosis.	Anderson et al. (2022) [14]
Relative Contraindication	Uncontrolled hypertension (SBP >180 mmHg or DBP >110 mmHg).	Optimise medications; start at 40% LOP; monitor BP	Nascimento et al. (2022) [13]

		for first 3 sessions.	
Monitoring Requirement	Significant postoperative oedema (limb circumference change >2 cm).	Re-measure LOP before every session – oedema significantly alters required pressure.	Wilkinson et al. (2019) [12]

7. Limitations, Research Gaps, and Future Directions

Despite current evidence, the blood flow restriction literature faces critical limitations. Protocol heterogeneity prevents direct study comparisons, while the reliance on isolated strength metrics fails to capture multidimensional functional recovery. Additionally, there is a lack of human biopsy studies confirming molecular mechanisms and a complete absence of health-economic analyses. Future research must prioritise multicentre pragmatic trials with standardised protocols, long-term follow-up studies extending beyond two years, and the development of evidence-based safety screening tools to firmly establish this modality as a definitive standard of care. Furthermore, it is important to acknowledge that this specific manuscript is a narrative review, which inherently carries limitations related to non-systematic search methodologies and potential selection bias.

8. Conclusions

Blood flow restriction training is a proven, mechanistically sound intervention that could safely bridge the gap in early postoperative rehabilitation. By utilising low mechanical loads to trigger profound physiological adaptations, it may effectively prevents muscle atrophy and accelerates recovery, most notably following anterior cruciate ligament reconstruction. Supported by automated calibration systems and expanding clinical evidence across diverse orthopaedic procedures, this modality could become a definitive standard of care.

Author Contributions

Conceptualization: Bartosz Rodziewicz, Mateusz Fidut; Methodology: Bartosz Rodziewicz; Investigation: Bartosz Rodziewicz, Mateusz Fidut, Mikołaj Kacperski; Writing - Original Draft Preparation: Bartosz Rodziewicz; Writing - Review and Editing: Mateusz Fidut, Mikołaj

Kacperski; Supervision: Mateusz Fidut. All authors have read and agreed to the published version of the manuscript.

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During the preparation of this manuscript, the authors used a large language model (Gemini 3.1 Pro) for linguistic and stylistic refinement. Following its use, the authors critically reviewed all stylistically enhanced text and take full responsibility for the accuracy, integrity, and scientific validity of the publication.

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