Effectiveness of Blood Flow Restriction Training in Early ACL Rehabilitation

1. Lay summary

Injuries to the anterior cruciate ligament (ACL) are among the most frequent musculoskeletal injuries, particularly in athletes and those who are physically active. Such injuries frequently necessitate surgical repair along with a systematic rehabilitation plan. A key difficulty in initial rehabilitation is regaining quadriceps muscle strength while avoiding undue strain on the healing graft. Weakness in the quadriceps muscle frequently occurs following surgery and may slow down recovery, lower functional capability, and heighten the risk of re-injury. Traditionally, to enhance muscle strength and size, strengthening exercises demand moderate to heavy weights. Nonetheless, during the initial period post-surgery, patients might struggle with such loads because of pain, swelling, and surgical restrictions. This generates a demand for different rehabilitation techniques that can effectively enhance muscle strength with reduced loads.

Blood Flow Restriction (BFR) training is an innovative method that entails placing a cuff around the upper limb to partially limit blood circulation while exercising. This enables patients to engage in low-load workouts while still experiencing muscle changes comparable to high-load training. BFR has attracted interest in musculoskeletal physiotherapy for its ability to improve recovery while minimising joint strain. This review seeks to assess the efficacy of BFR training in enhancing quadriceps strength, muscle size, and functional results in individuals undergoing early ACL rehabilitation. The results will assist clinicians in evaluating whether BFR can be safely and effectively incorporated into rehabilitation programs to enhance patient outcomes and speed up recovery.

2. Background

2.1 ACL Injury and Rehabilitation

The anterior cruciate ligament (ACL) is an essential stabilising component of the knee joint, tasked with preventing the tibia's forward movement in relation to the femur and playing a crucial role in rotational stability. It is vital for dynamic joint management during activities like running, jumping, and pivoting. ACL injuries are especially common in sports that require rapid deceleration, cutting actions, and directional changes, including football, basketball, and skiing. After an ACL injury, numerous patients have surgical reconstruction (ACLR) performed to regain mechanical stability. Nonetheless, restoring structural integrity does not

mean achieving complete functional recovery. Rehabilitation after surgery is crucial for restoring strength, neuromuscular coordination, and functional abilities. Initial rehabilitation usually emphasises decreasing joint swelling, regaining range of motion (ROM), and re-engaging the quadriceps muscle. Even with improvements in surgical methods and recovery plans, weaknesses in muscle strength and neuromuscular control frequently endure long after the operation. This underscores the significance of enhancing rehabilitation methods to boost patient results and lower the chance of reinjury.

2.2 Quadriceps Weakness After ACL Reconstruction

Weakness in the quadriceps is a highly prevalent and clinically important limitation that occurs after ACL reconstruction. This deficiency is mainly due to arthrogenic muscle inhibition (AMI), a reflexive neural suppression that restricts voluntary engagement of the quadriceps muscle. AMI is affected by elements like joint inflammation, discomfort, and changed sensory input from the damaged knee. Along with neural inhibition, muscle atrophy quickly happens because of decreased loading and lack of use during the early post-operative phase. Research has indicated that notable decreases in the quadriceps cross-sectional area can happen within weeks after surgery. This mix of neural and morphological alterations leads to extended strength impairments.

Ongoing weakness in the quadriceps has been closely linked to unfavourable functional results, including decreased ability in tasks like stair climbing, squatting, and running. Additionally, it has been associated with changed movement patterns, including reduced knee flexion during landing, which could heighten the risk of subsequent ACL injury or injury on the opposite side (Kotsifaki et al., 2023). Thus, timely and efficient approaches to regain quadriceps strength are crucial. Nonetheless, accomplishing this during the initial phases of rehabilitation continues to pose a considerable clinical challenge because of restrictions in loading capacity.

2.3 Limitations of Traditional Strength Training

Conventional resistance training guidelines suggest that muscle hypertrophy and strength improvements are best achieved with moderate to high mechanical loads, generally at least 60–70% of one-repetition maximum (1RM). These loads are essential for creating adequate mechanical tension and promoting muscle protein synthesis. Nonetheless, in the realm of early ACL rehab, implementing such loads is frequently impractical. Patients often encounter pain,

joint swelling, and decreased capacity for loading, which restricts their capability to engage in high-intensity workouts. Moreover, too much loading in the initial phase can impose unnecessary stress on the healing graft, possibly jeopardising surgical results.

Consequently, rehabilitation programs frequently depend on low-load exercises, which might not be adequate to avert muscle atrophy or facilitate considerable strength improvements. This may result in extended recovery durations and less-than-ideal functional results. These constraints emphasise a significant shortcoming in rehabilitation practice: the necessity for interventions capable of promoting muscle changes without placing substantial mechanical stress on the joint. This has resulted in a growing interest in alternative methods like Blood Flow Restriction training.

2.4 Blood Flow Restriction Training

Blood Flow Restriction (BFR) training has developed into a novel and clinically significant method in musculoskeletal rehabilitation. The method entails using an inflatable cuff or tourniquet on the upper part of the limb, which limits venous drainage while preserving arterial supply. This regulated blockage induces a hypoxic and metabolically challenging situation in the active muscle during physical activity. Consequently, even light-load exercises (20–30% 1RM) can trigger physiological reactions akin to those seen with high-load resistance training.

From a clinical viewpoint, BFR provides a distinct benefit in initial ACL rehab. It enables patients to carry out strengthening exercises with light weights, thus reducing strain on the joint and safeguarding the surgical graft, while also fostering muscle hypertrophy and increasing strength. Moreover, BFR training is fairly simple to carry out in a clinical environment and can be incorporated into current rehabilitation programs. Nevertheless, suitable usage, such as accurate cuff positioning and pressure control, is crucial to guarantee safety and efficacy.

2.5 Mechanism of Action

The efficacy of BFR training is supported by several interrelated physiological processes. A key mechanism is metabolic stress, resulting from the build-up of metabolites like lactate, hydrogen ions, and inorganic phosphate in the muscle. This metabolic setting activates anabolic signalling pathways that encourage muscle growth. Another important process is the heightened recruitment of fast-twitch (Type II) muscle fibres. In typical situations, low-load

workouts mainly activate slow-twitch fibres. Nonetheless, the hypoxic environment induced by BFR intensifies fatigue in these fibres, causing quicker activation of fast-twitch fibres, which possess a higher capacity for hypertrophy.

Furthermore, BFR training has been demonstrated to promote the release of anabolic hormones such as growth hormone and insulin-like growth factor-1 (IGF-1), which are important for muscle repair and regeneration (Hughes et al., 2021). Cellular expansion, resulting from fluid buildup in the muscle, might also aid in anabolic signalling. Crucially, these mechanisms enable notable muscle adaptations to take place without heavy mechanical loads, rendering BFR especially appropriate for groups with restricted loading ability, like post-operative ACL patients.

2.6 Evidence Supporting BFR in ACL Rehabilitation

The expanding research supporting BFR training in ACL rehabilitation offers a solid basis for its clinical use. Recent systematic reviews and meta-analyses have shown that BFR training can significantly enhance quadriceps strength, muscle mass, and functional results. Fraca-Fernandez et al. (2024) indicated that BFR training greatly enhanced quadriceps strength and functional capabilities in patients prior to and following ACL reconstruction. Their meta-analysis emphasised the ability of BFR to reduce muscle atrophy in the initial phase of rehabilitation. Colombo et al. (2024) similarly discovered that BFR training yielded results similar to conventional high-load resistance training, even with much lighter weights. This discovery is especially significant in early rehabilitation, where heavy-load training is frequently not recommended.

Gopinatth et al. (2025) further supported these results, showing that BFR training boosts recovery and speeds up functional enhancements after ACL reconstruction. Their examination of randomised controlled trials indicated that BFR could promote a quicker return to activity. Furthermore, García-Rodríguez et al. (2024) noted enhancements in pain levels, muscle performance, and overall recovery results with BFR interventions. These results indicate that BFR could offer both physiological and clinical advantages.

Nevertheless, in spite of these encouraging findings, various constraints persist in the existing literature. Variations in BFR protocols, such as discrepancies in cuff pressure, choice of exercises, and duration of training, complicate the creation of standardised guidelines.

Additionally, future research is needed to explore long-term results and safety aspects. In general, although existing evidence strongly backs the use of BFR alongside conventional rehabilitation, additional high-quality studies are necessary to enhance its use and set optimal practice guidelines.

2.7 Search Strategy

A literature search will be conducted using the following databases:

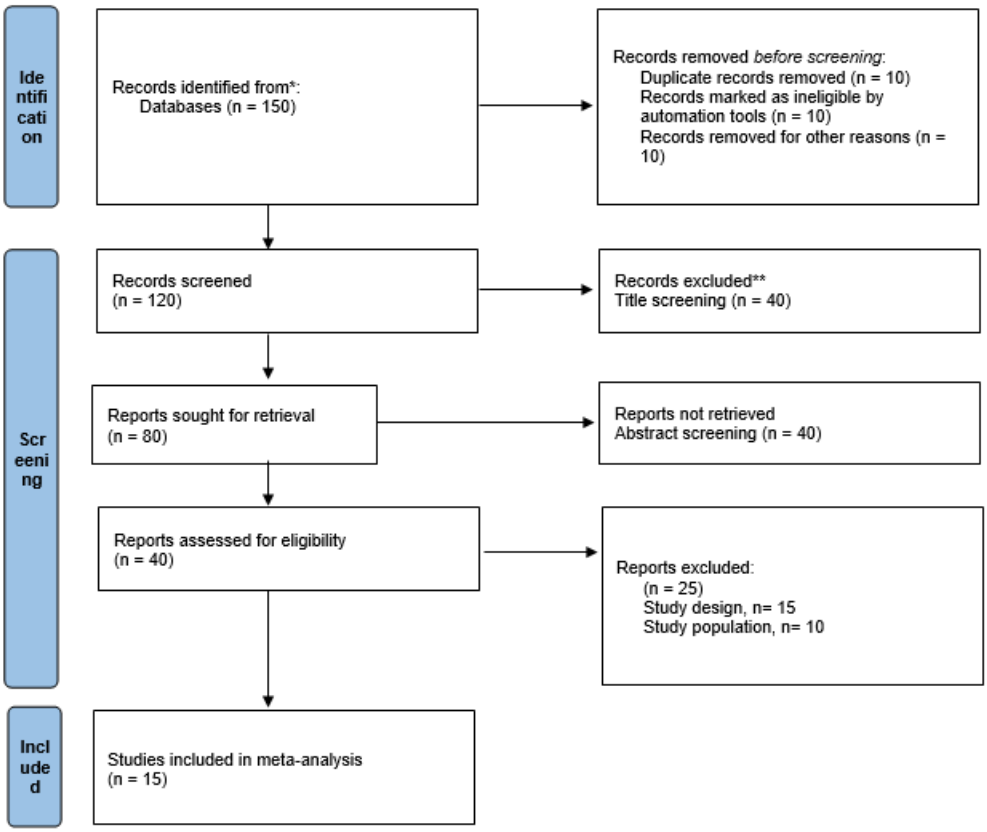
- PubMed
- Scopus

Keywords will include:

- “Blood Flow Restriction”
- “ACL Reconstruction”
- “Quadriceps Strength”

Boolean operators (AND, OR) will be used to refine the search. Filters will be applied to include studies published between 2020 and 2025, focusing on randomised controlled trials and systematic reviews.

2.8 PRISMA Flow Diagram



2.9 PICO Framework

- **Population:** Patients after ACL reconstruction
- **Intervention:** Blood Flow Restriction training
- **Comparison:** Conventional rehabilitation
- **Outcome:** Quadriceps strength, muscle hypertrophy, functional recovery

3. Literature review

The growing body of evidence backing Blood Flow Restriction (BFR) training in the rehabilitation of anterior cruciate ligament (ACL) offers a solid basis for its clinical use in musculoskeletal physiotherapy. Recent systematic reviews and meta-analyses consistently show that BFR training can greatly improve quadriceps strength, muscle growth, and functional results, especially in the initial phases of rehabilitation when conventional high-load resistance training is usually not recommended. Fraca-Fernandez et al. (2024) performed an extensive

meta-analysis investigating the impacts of BFR training on ACL patients both before and after surgery. The results showed that BFR training notably enhanced quadriceps strength and functional ability compared to traditional rehabilitation methods. Significantly, the authors highlighted the possible function of BFR in reducing muscle atrophy during the initial recovery phases, a stage marked by diminished loading capacity and a heightened risk of disuse-related muscle loss. This underscores the clinical significance of BFR as a strategy that can connect immobilization and gradual loading.

In a similar vein, Colombo et al. (2024) indicated that BFR training yielded results similar to conventional high-load resistance training, even when employing much lighter weights. This result is especially significant in the realm of early ACL rehabilitation, as excessive mechanical stress might jeopardize graft integrity and prolong recovery. BFR's capacity to produce similar strength and hypertrophy changes through low-load workouts endorses its position as an effective and safer substitute to traditional strengthening methods in the early post-operative period. The growing collection of studies backing Blood Flow Restriction (BFR) training in anterior cruciate ligament (ACL) rehabilitation offers a solid basis for its use in musculoskeletal physiotherapy. Recent systematic reviews and meta-analyses consistently show that BFR training can markedly improve quadriceps strength, muscle hypertrophy, and functional outcomes, especially in the early phases of rehabilitation when traditional high-load resistance training is frequently inadvisable.

Fraca-Fernandez et al. (2024) carried out an extensive meta-analysis exploring the impacts of BFR training in populations with ACL injuries both before and after surgery. Their research showed that BFR training notably enhanced quadriceps strength and functional performance in comparison to traditional rehabilitation methods. Crucially, the authors highlighted the possible function of BFR in diminishing muscle atrophy in the initial phases of recovery, a timeframe marked by decreased loading ability and heightened risk of muscle loss due to disuse. This underscores the clinical importance of BFR as a method that can connect immobilisation with progressive loading. In a similar vein, Colombo et al. (2024) found that BFR training yielded results similar to conventional high-load resistance training, even while using substantially lighter weights. This discovery is especially significant in the realm of early ACL rehabilitation, where excessive mechanical stress could jeopardise graft integrity and hinder recovery. The capacity of BFR to produce similar strength and hypertrophy responses with

low-load exercises reinforces its position as a practical and safer substitute for traditional strengthening methods in the early post-operative period.

From a physiological standpoint, earlier studies provide strong support for the mechanisms underlying BFR training. Hughes et al. (2021) showed that low-load BFR training can lead to comparable gains in muscle strength and hypertrophy as high-load resistance training in clinical groups. This offers a solid theoretical foundation for employing BFR in initial rehabilitation, where substantial mechanical loads are impractical. The capacity to obtain significant muscle changes via metabolic stress instead of mechanical load signifies a major progress in rehabilitation methods. Even with the expanding pool of evidence, numerous significant limitations and gaps persist in the literature. A major challenge is the absence of standardisation in BFR protocols. Differences in cuff width, pressure for occlusion, choice of exercises, frequency of training, and length of sessions complicate the establishment of definitive clinical guidelines. For instance, certain studies employ constant occlusion pressures, whereas others apply a proportion of limb occlusion pressure (LOP), potentially leading to varying physiological responses and results. This lack of consistency restricts the capability to directly compare studies and may impact the trustworthiness of findings.

A significant drawback is the comparatively brief follow-up period in numerous studies. Although short-term gains in strength and function are well-established, there is limited proof concerning the long-term maintenance of these advantages. It is still uncertain if the benefits gained from BFR training lead to better long-term functional results, lower rates of reinjury, or improved performance in returning to sports. Longitudinal studies are thus it is necessary to fill these gaps. Safety factors are also essential in the clinical use of BFR training. While current evidence indicates that BFR is typically safe when used properly, data on its application in individuals with preexisting cardiovascular or vascular issues is scarce. Possible hazards, like high occlusion pressure or incorrect cuff positioning, underscore the need for clinician education and meticulous patient choice. This emphasizes the necessity for standardized guidelines to guarantee safe and effective execution.

Additionally, most current research mainly emphasizes muscle strength and hypertrophy results, while relatively fewer investigations assess functional performance, neuromuscular control, return-to-sport standards, and rates of reinjury. These results are crucial in ACL rehabilitation, as effective recovery encompasses not just strength improvements but also movement quality and functional stability. Future studies should consequently take a more

comprehensive approach by integrating both biomechanical and functional outcome metrics. A key factor to consider is the likelihood of publication bias in the existing literature. Research showing favourable results tends to be published more frequently, potentially resulting in an inflated perception of the efficacy of BFR training. Moreover, variations in study quality, such as changes in randomisation, blinding, and reporting standards, can affect the dependability of results. This highlights the significance of critical evaluation when analysing results.

In conclusion, the existing research offers robust proof endorsing BFR training as a valuable complement to conventional rehabilitation in the initial stages of ACL reconstruction. Its capacity to promote muscle strengthening with minimal loads renders it especially beneficial during the initial post-operative period, when loading capabilities are restricted. Nonetheless, the differences in protocols, methodological constraints, and absence of long-term data emphasise the necessity for careful interpretation and additional investigation. This systematic review seeks to fill these gaps by combining existing evidence, assessing the efficacy of BFR training, and offering clinically pertinent insights for its use in musculoskeletal physiotherapy. In doing so, it aims to enhance the development of more efficient, evidence-driven rehabilitation strategies for individuals undergoing ACL reconstruction.

4. Purpose

The purpose of this review is to evaluate the effectiveness of blood flow restriction training in improving quadriceps strength and functional outcomes during early ACL rehabilitation.

Objectives:

- To assess the impact of BFR on muscle strength
- To compare BFR with conventional rehabilitation
- To evaluate functional outcomes

Hypothesis:

BFR training will produce comparable or superior outcomes compared to traditional rehabilitation methods.

4. Methods

4.1 Study Design

This study will be conducted as a review following PRISMA guidelines.

4.2 Inclusion Criteria

- Studies published from 2020 onwards
- ACL reconstruction patients
- BFR intervention
- RCTs and systematic reviews
- Outcomes related to strength and function

4.3 Exclusion Criteria

- Non-musculoskeletal conditions
- Case reports
- Animal studies
- Studies without BFR intervention

4.4 Data Extraction

Data will be extracted on:

- Sample size
- Intervention protocols
- Outcome measures
- Results

4.5 Data Analysis

A narrative synthesis will be conducted due to heterogeneity in study designs and interventions.

4.6 Outcome Measures

- Quadriceps strength
- Muscle hypertrophy

- Functional scores (KOOS, WOMAC)

5. Ethics

Since this study is structured as a systematic review, it does not include direct engagement with human subjects. Thus, formal ethical approval from an institutional review board is typically unnecessary. Nonetheless, commitment to ethical standards is vital to maintain the integrity, transparency, and trustworthiness of the research process. The research will adhere to recognised ethical principles, such as honesty, impartiality, clarity, and responsibility. All data sources will originate from previously published research, with proper credit provided via precise and consistent citation in Harvard style. This guarantees that intellectual property rights are honoured and that the likelihood of plagiarism is reduced.

An important ethical aspect of systematic reviews is the precise and impartial portrayal of available evidence. The researcher will make sure that data extraction is performed methodically and impartially, avoiding any selective reporting or alteration of results. To reduce the risk of bias, a clear and systematic methodology will be utilised, encompassing predetermined inclusion and exclusion standards, an extensive search strategy, and the application of established critical appraisal instruments like the PEDro scale and CASP checklist. Additionally, the research will follow the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, which enhance transparency and reproducibility in systematic reviews. Utilising a PRISMA flow diagram will guarantee that the study selection process is well-documented, minimising the likelihood of selection bias and improving methodological rigour.

While concerns about confidentiality are low due to the utilisation of publicly accessible data, ethical obligations continue to involve the correct management and interpretation of the data. The researcher will guarantee that results from the included studies are reported accurately and in context, preventing misinterpretation or excessive generalisation of the findings. Another significant ethical factor is the handling of bias. Possible sources of bias in systematic reviews consist of publication bias, selection bias, and bias from reviewers. To tackle these issues, the research will encompass an extensive search through various databases, well-established eligibility criteria, and an open selection procedure. Limitations present in the studies included will be recognized and critically examined where applicable.

The investigator is also tasked with making sure that the results of this review are conveyed in a clinically relevant and balanced way. Exaggerating the benefits of methods like Blood Flow Restriction training without adequate evidence may result in unsuitable clinical use. Consequently, conclusions will be reached carefully, grounded in the strength and quality of the evidence that is available. Ultimately, this research is in accordance with evidence-based practice principles in physiotherapy, seeking to integrate existing studies to guide clinical decision-making. By upholding strong ethical standards during the research process, this systematic review aims to responsibly enhance the development of musculoskeletal physiotherapy practice.

6. Dissemination

Sharing research findings is an essential part of the research process, making sure that the knowledge produced from this systematic review is efficiently conveyed to pertinent stakeholders and supports evidence-based practice in musculoskeletal physiotherapy. The results of this research will be shared via various platforms to enhance its influence on clinical practice and subsequent studies. The outcomes of this systematic review will initially be showcased in an academic environment, for example, as part of a submission for a postgraduate physiotherapy program. This guarantees that the study fulfils the necessary academic criteria and aids in academic advancement. Furthermore, the results could be shared at academic conferences or seminars focused on musculoskeletal physiotherapy, sports rehabilitation, or orthopaedics. These platforms offer avenues for peer evaluation, thoughtful debate, and information sharing between clinicians and researchers.

Secondly, dissemination via peer-reviewed journals will be evaluated, especially those emphasising sports medicine and rehabilitation. Publishing in a reputable journal would enable the results to be shared with a broader audience, such as clinicians, researchers, and policymakers. This is especially crucial considering the increasing attention on Blood Flow Restriction (BFR) training as a recovery method in ACL surgeries. Disseminating results via peer-reviewed avenues further boosts the research's credibility and validity. From a clinical standpoint, the results of this review hold immediate relevance for physiotherapy practice. Consequently, sharing information with practicing clinicians is crucial. This can be accomplished via professional networks, workshops, or ongoing professional development (CPD) activities. Translating research results into actionable suggestions allows

physiotherapists to incorporate evidence-based methods like BFR training into rehabilitation plans, thereby enhancing patient outcomes.

Furthermore, digital platforms can be employed to improve accessibility and expand reach. Sharing knowledge quickly can be enhanced through online channels like professional forums, webinars, and platforms related to physiotherapy. This is especially significant in contemporary healthcare environments, where digital communication increasingly impacts professional training and cooperation. Considering dissemination to a non-academic audience is also vital. A concise summary of the results (public dissemination) can be provided to patients or the wider community to enhance awareness of rehabilitation choices after ACL injury. This is consistent with the ideals of patient-focused care and facilitates informed choices. Ultimately, the distribution process will guarantee that results are communicated accurately and free from embellishment. The study's limitations will be explicitly recognized to prevent misinterpretation or incorrect application in clinical practice. Through a transparent and accountable approach to dissemination, this research seeks to significantly aid in the development of evidence-based musculoskeletal physiotherapy.

References

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