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Effect of Blood Flow Restriction Training on Quadriceps Muscle Performance Following ACL Reconstruction: A Systematic Literature Review

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Abstract

Background: Owing to disadvantage of conventional rehabilitation, there is need for specific intervention to overcome muscle atrophy or deficits following anterior cruciate ligament reconstruction (ACLR). This clinically significant quadriceps muscle deficiency led to knee pain and biochemical disruptions.

Objective: The study aimed to determine the effectiveness of blood flow restriction therapy (BFRT) in the enhancement of clinical outcomes such as muscle strength, muscle size, patient-reported outcomes, and functional performance.

Methodology: A systematic review was conducted following Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) 2020 guidelines. The literature was searched on PubMed, Scopus and Cochrane library. The search was limited to only articles written in English and published between 1st January 2020 and 31st August 2025. Risk of bias (ROB) was assessed using Cochrane Risk of Bias (ROB) 2.0. The narrative synthesis and data driven iterative approach was used to synthesize evidence. P-value < 0.05 was taken to determine statistical significance.

Results: The initial database search yielded 105 articles. After removing (20) duplicates, the titles and abstracts of 85 articles were screened for relevance. Sixty (65) articles were excluded due to irrelevant titles and abstracts. One article did not retrieve full text. The remaining full text of 19 articles was assessed, and 7 met eligibility criteria. The 7 RCTs were included to synthesize evidence.

Conclusion: BFRT reported mixed effectiveness for patients underwent ACLR. One model for BFRT incorporation in ACLR rehabilitation emphasize its use in the early post-operative period (2-8 weeks) with low-load resistance training (<30% 1RM) and then implementing it mid-term when high load training (>70% 1RM) is not tolerated. There is clear evidence that 80% or higher AOP/LOP is the ideal dose for muscle strength and size. However, evidence also synthesized that BFRT as an adjuvant to high-intensity protocols reduce knee pain initially but no long-term outcomes. Some RCTs also examined that BFRT did not provide superior role to conventional rehabilitation (pre- or peri). Therefore, future RCTs are emphasized to validate the findings.

Keywords: Anterior Cruciate Ligament, ACL Reconstruction, Blood Flow Restriction Training, Quadriceps muscle, Muscle performance.

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Introduction

Anterior Cruciate Ligament (ACL) surgeries is a normal procedure done in individuals such as e.g., athletes who desire to have the knee stability regained and thus be able to engage in physically demanding activities [1]. However, the way back to perfect health is quite frequently made tricky by the realization that a severe post-surgical issue through recurrent feebleness and atrophy of the mass muscle of the thigh, more particularly, the quadriceps and hamstring muscle [2]. This deficit is not an overnight issue but can potentially outlast the post first rehabilitation phase and continue to pose a great challenge to the good and safe recovery to sport and may well result into additional injury in the future [3].

Owing to drawback of conventional rehabilitation courses, there is need for specific intervention to overcome them. Bregenhof et al. (2023) referred to a sample of 12-24-month ACLR patients who continued to complain about clinically significant hamstring deficiencies with regard to hamstring strength following a hamstring autograft. The authors demonstrated that very specific and closely observed strength program that emphasizes on maximal isometric knee flexor muscle strength at this late stage, is superior to routine home-based exercises, which point to the fact that routine rehabilitation is not always sufficient in regaining muscle strength fully [4]. This is a critical long term functional deficiency highlighting the urgent need of more functional interventions that can overcome muscular weakness and atrophy during the earlier critical post-operative periods.

Blood flow restriction training (BFRT) plays role to increase in muscular power and size (hypertrophy). BFRT involves the act of inflating an airtight cuff over the more distal limb to partially limit the arterial inflow and entirely prevent the venous outflow during exercise, leading to hypoxic effect in the muscle to trigger metabolic and cellular activities for muscle fibers building despite extreme low exercise loads [5,6]. The implication of BFRT beneficial particularly for patients where high resistance and stressful exercise may be frequently contraindicated by pain and joint stress [7].

This literature review is aimed at synthesizing and critically reviewing the findings of included randomized controlled trials (RCTs) about the effectiveness of BFRT in the enhancement of clinical outcomes such as muscle strength, muscle size, patient-reported outcomes, and functional performance.

Material and Methods

Study Design and Protocol Registration

A systematic review will be conducted following Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) 2020 guidelines [8].

PICOST Framework

The text words and MeSH terms presented in Table 1 were used to devise research question using PICOST framework.

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Table 1: PICOST Framework

PICOST Framework	Text Words (domains)	MeSH terms
P (Population):	Adult Patients underwent ACLR	("Anterior Cruciate Ligament Reconstruction"[Mesh]) OR "Adult"[Mesh]
I (Intervention):	Blood Flow Restriction training	"Blood Flow Restriction Therapy"[Mesh]
C (Comparison):	Physical therapy rehabilitation including strength exercises, range of motion exercises, weight training, resistance training.	"Physical and Rehabilitation Medicine"[Mesh] OR "Exercise Therapy"[Mesh]
O (Outcome):	Quadriceps muscle performance such as strength, power, hypertrophy	"Quadriceps Muscle"[Mesh], "Muscle Strength"[Mesh]
S (Study Design):	Randomised controlled trials	("Randomized Controlled Trial" [Publication Type])
T (Time):	1st January 2020 to 31st August 2025	-

Research Question

How effective is blood flow restriction therapy as compared to physical therapy rehabilitation to increase quadriceps muscle performance after ACLR?

Outcome Measures

The primary outcomes quadriceps strength (muscle force output), functional knee performance, muscle hypertrophy will be measured using following outcome measures presented in Table 2.

Table 2: Outcome measures

Primary Outcomes	Outcome Measures
Quadriceps strength	Manual Muscle Testing (MMT), Dynamometer
Functional Performance	Timed Up and Go (TUG) Test, 6-minute Walk test (6-MWT)
Muscle Hypertrophy	ultrasound imaging or MRI

Search Strategy

The aforementioned keywords, text words and MeSH terms used with appropriate Boolean operators to search literature. Only peer-reviewed journals' published studies were sought from PubMed, Cochrane library and Scopus (Last Searched 5th to 10th September, 2025). The review was restricted or limited search to only clinical trials written in English and published from 1st January 2020 to 31st August 2025.

Eligibility Criteria

The eligibility criteria are presented in Table 3.

Table 3: *Eligibility Criteria*

Inclusion Criteria	Exclusion Criteria
Studies focusing on adult ACL reconstruction irrespective of the associated comorbidities.	Studies focusing on healthy individuals or on conservative treatment without knee surgical procedure.
Studies focused blood flow restriction therapy.	Studies without blood flow restriction therapy.
Studies focused on quadriceps muscle performance such as muscle strength, power and thickness.	Studies focused on other than quadriceps muscle.
Randomised controlled trials (RCTs)	Non-RCTs, Editorials, letter of opinion, review papers (narrative or literature)
Studies which were written in English language and published in peer-reviewed sources.	Studies published in non-peer-reviewed sources such as preprints, conference abstracts, or articles with insufficient methodological rigor.

Selection Process

Clinical trials were screened independently by authors (AM, MHFK, MA, MS). Screening conflict was resolved by consensus. The selection process carried out using PRISMA 2020 statement guidelines [8] in two phases; First, title and abstract screening. Second, full text screening and eligibility check (See, Figure 1).

Data Extraction

Data was extracted independently by authors (AM, MHFK, MA, MS) using standardized excel spreadsheet following Cochrane guidelines for data extraction for systematic review [9]. For example, author, year, study design, sample size, gender (%), intervention group, control group, BFR protocol, restriction characteristics, main findings with statistical significance (p-value) were extracted in excel spreadsheet and then will be transferred in form of table into MS docx file.

Methodological Quality Assessment

Risk of bias (ROB) was assessed using [10] . All clinical trials were categorised as low, some concerns and high ROB as per Cochrane guidelines.

Data Synthesis

Data was synthesised using a narrative and iterative data-driven synthesis approach [11]. But the included trials contained statistical data to support the evidence using outcomes strength, muscle mass, performance enhancement e.g., improvement in function, and strength of Quadriceps muscle. Moreover, $p < 0.05$ was taken to determine the statistical significance.

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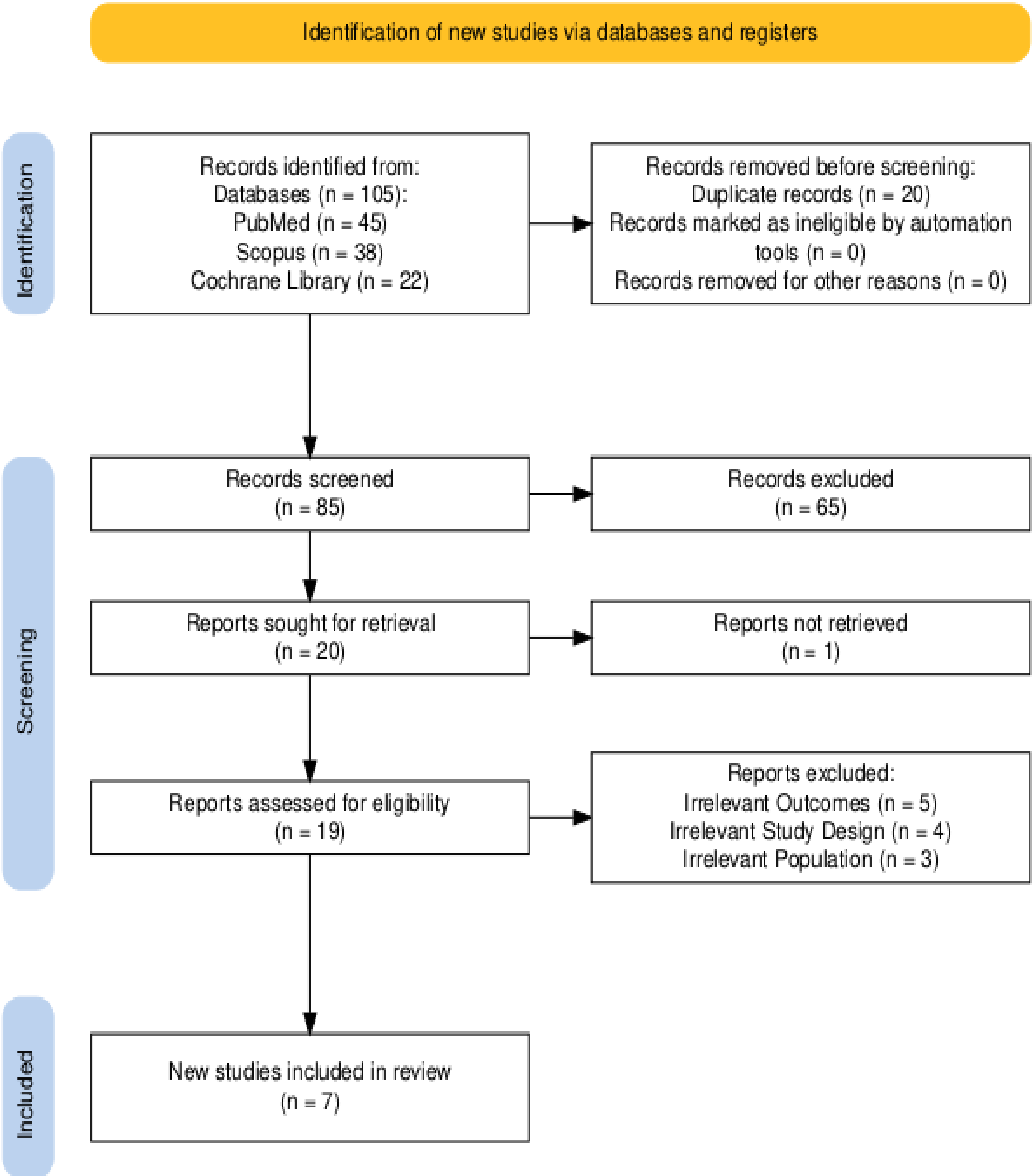

Figure 1: *PRISMA Flow Chart*

Results

Selection Process of Studies

The initial database search yielded 105 articles. After removing (20) duplicates, the titles and abstracts of 85 articles were screened for relevance. Sixty (65) articles were excluded due to irrelevant titles and abstracts. One article did not retrieve full text. The full text of 19 articles was assessed, and 7 met eligibility criteria. Seven (07) randomized controlled trials were included after selection following PRISMA guidelines. The systematic review included 236 adult ACLR patients. There are huge heterogeneity and variability observed between methodologies used. The findings of each RCT are illustrated in Table 4.

Table 4: Characteristics of Included RCTs

Study (Author, Year)	Study Design & Sample Size (n)	Intervention Timing	BFRT Protocol	Control/Comparator Group	Primary Outcome Measures	Findings (p-value)
Curran et al. (2020) [12]	RCT (n=34)	Mid-term post-operative (10-18 weeks)	80% LOP with high-intensity (70% 1RM) exercise.	High-intensity (70% 1RM) concentric or eccentric exercise.	Quadriceps peak torque, muscle volume, IKDC scores.	No significant differences were found between groups for any outcome measures at either time point ($P > 0.05$)
De Melo et al. (2022) [13]	RCT (n=28)	Early post-operative (up to 12 weeks)	80% LOP with low-load (30% 1RM) exercise.	High-load (70% 1RM) exercise.	Quadriceps & hamstring strength, PROs (KOOS, IKDC, Lysholm).	a statistical difference was observed in the quadriceps with an increase in muscle strength ($p < 0.01$) after 12 weeks.
Khalil et al. (2023) [14]	Double-Blinded RCT (n=36)	Early post-operative (1-12 weeks)	80% LOP with conventional rehab exercises.	Conventional Rehabilitation Protocol (CRP) only.	Knee pain via VAS.	Adding BFRT to conventional rehabilitation protocol was not superior to conventional rehabilitation alone on knee pain among ACLR patients ($p > 0.05$).
Okoroha et al. (2023) [15]	RCT (n=46)	Peri-operative (2 weeks pre-op to 12 weeks post-op)	80% LOP with pre- and post-operative exercises.	Standard pre- and post-operative rehab.	Isometric quadriceps torque, PROs (PROMIS, IKDC).	Integrating BFRT into perioperative PT protocols led to improved strength and increased PROs at 6 weeks after ACLR ($p < 0.05$). No differences in strength were found

Tramer et al. (2023) [16]	RCT (n=45)	Pre-operative (2 weeks)	Home-based 80% LOP with standardized pre-habilitation exercises.	Standardized home-based pre-habilitation only.	Quadriceps peak force, PROs (PROMIS).	No difference ($p < 0.05$) in quadriceps circumference, strength, or patient reported outcomes were found between the BFR and the control group. The home-based BFR pre-habiliation protocol was found to be feasible, accessible, and well tolerated by patients.
Xuefeng Li et al. (2023) [17]	RCT (n=30 randomized; n=23 completed)	Mid-term post-operative (starting >8 weeks post-op)	40% vs. 80% AOP with low-intensity rehab.	Conventional quadriceps rehab (no BFR).	Isokinetic knee extension strength, quadriceps muscle thickness, IKDC.	Combination of BFR and low-intensity quadriceps femoris training can effectively improve the muscle strength and thickness of knee extensors in participants with ACLR ($p < 0.05$).
Sevinc et al. (2025) [18]	Single-Blinded RCT (n=24)	Mid-term post-operative (4-12 weeks)	80% LOP BFRT with Cross-Education (CE) on the uninjured limb.	CE on uninjured limb only.	Quadriceps isometric strength, quadriceps muscle thickness.	In Group 1, the limb symmetry index for quadriceps strength increased from 49.3% to 71.7%, while in Group 2, it increased from 50.9% to 75.2%.

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* Arterial Occlusion Pressure, Randomized Controlled Trial (RCT), Limb Occlusion Pressure (LOP), Patient Reported Outcomes Measurement Information System, International Knee Documentation Committee (IKDC), Visual Analogue Scale (VAS), Knee injury and Osteoarthritis Outcome Score (KOOS). Repetition Maximum (RM).

Critical Appraisal of Included RCTs

The overall risk of bias (ROB) of only one RCT is low ROB and 5 RCTs were reported as some concerns. However, only one RCT reported as high ROB. The ROB was down rated due to majority of 6 RCTs demonstrated some concerns to high ROB in D2 domain(bias due to deviations from intended intervention). Hence, the some concerns ROB indicate that the evidence is somehow valid but it needs further validation and it should be intrepretated with caution to imply all findings in clinical settings (Figure 2).

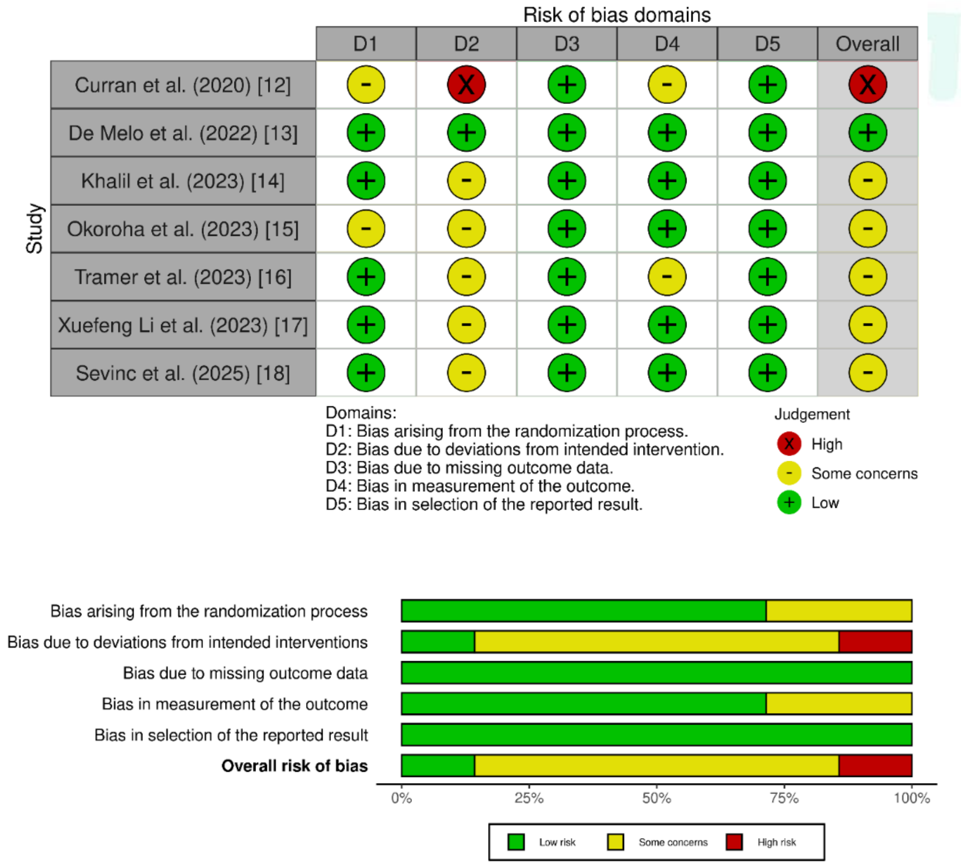

Figure 2: *Summary and Traffic Plots Illustration using Cochrane Risk of Bias 2.0*

Discussion on Synthesis of findings about BFRT effectiveness

The review synthesizes the collective evidence from the included studies, providing a comprehensive assessment of BFRT's effectiveness in ACL reconstruction rehabilitation. The findings are organized thematically around key clinical outcomes—muscle strength, muscle size, and patient-reported measures—to

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build a clear, evidence-based picture of BFRT's impact and to highlight areas of consensus and conflict within the current literature.

Impact on Muscle (Quadriceps and Hamstrings) Strength

The evidence regarding BFRT's ability to augment muscle strength recovery is notably mixed, with several studies reporting positive effects while an equal number find no significant additional benefit over comparator treatments. This discrepancy appears central to the debate over BFRT's clinical utility. Clinical trials reporting positive outcomes point toward significant, often rapid, strength gains.

De Melo et al. (2022) found that a low-load BFRT program was more efficient than a high-load exercise program for improving both quadriceps and hamstring muscle strength. Significant improvements in the BFRT group were noted for hamstrings at 8 and 12 weeks, and for quadriceps at 12 weeks post-surgery [13]. Xuefeng Li et al. (2023) demonstrated that BFRT combined with low-intensity training effectively improved knee extensor muscle strength. Notably, the group using a higher pressure (80% AOP) saw significantly greater improvements in isokinetic quadriceps strength at both 60°/s and 180°/s compared to both a 40% AOP group and a no-BFR control group [17]. Okoroha et al. (2023) reported a transient but significant early benefit. At 6 weeks post-operatively, the peri-operative BFRT group demonstrated significantly greater quadriceps strength (Quadriceps Index of 57% vs. 40%) compared to the control group. However, this advantage was not maintained, and no significant differences in strength were observed between the groups at the 3- or 6-month follow-up points [15].

In direct contrast, several well-designed trials found that BFRT provided no additive strength benefits. Curran et al. (2020) concluded that an 8-week BFRT intervention, when combined with high-intensity resistance exercise, did not significantly improve isometric or isokinetic quadriceps muscle strength compared to high-intensity exercise alone [12]. Tramer et al. (2023) evaluated a 2-week, home-based pre-operative BFRT program and found no significant differences in quadriceps strength between the BFRT and control groups on the day of surgery [16]. Sevinc et al. (2025) investigated the combination of BFRT with Cross-Education (CE)—training the uninjured limb to stimulate the injured limb—and found it was not effective. There was no significant group-by-time interaction or main group effect for quadriceps isometric strength, suggesting BFRT did not enhance the CE effect [18]. The contrast between these outcomes strongly suggests that BFRT's effect on strength is not universal, but highly dependent on moderating factors such as the timing and intensity of the accompanying exercise protocol.

Impact on Muscle Size (Atrophy and Hypertrophy)

Similar to the findings on muscle strength, the effect of BFRT on preserving or increasing muscle size (i.e., mitigating atrophy and promoting hypertrophy) is varied across the literature. A significant positive effect was reported by Xuefeng Li et al. (2023). Their study, which compared different BFRT pressures, found that the 80% AOP group experienced a significant increase in the thickness of the rectus femoris and vastus intermedius muscles compared to both the 40% AOP group and the control group. This finding suggests a dose-dependent relationship between BFRT pressure and hypertrophic response. Conversely, other studies failed to detect any BFRT-related benefits for muscle size [17]. Curran et al. (2020) reported no significant differences in the change in rectus femoris muscle volume between their four study groups (concentric, eccentric, and their BFRT counterparts) [12]. Similarly, Sevinc et al. (2025) found no significant group-by-time interaction for the thickness of the vastus medialis obliquus, rectus femoris, or vastus lateralis muscles, indicating that adding BFRT to a CE protocol did not provide additional benefits for muscle size [18]. This dose-dependent finding from Xuefeng Li et al., contrasted with the lack of effect in other studies, indicates that both BFRT pressure and its interaction with the primary intervention are critical variables influencing hypertrophic outcomes [17].

Impact on Patient-Reported Outcomes (PROs) and Knee Pain

The influence of BFRT on subjective outcomes, including functional questionnaires and pain perception, also varies. Positive findings for PROs were noted in two studies. De Melo et al. (2022) demonstrated that their BFRT group had significantly better scores on the KOOS (pain, symptoms, daily activities, quality of life), IKDC, and Lysholm questionnaires at various time points between 4 and 12 weeks [13]. Okoroha et al. (2023) also reported significantly better IKDC and PROMIS-Physical Function scores for the BFRT group at the 6-week post-operative mark, though these differences did not persist at 3 and 6 months. However, other studies found BFRT to be no more effective than the comparator [15]. Khalil et al. (2023) did not examine superior role of BFRT in reducing VAS score in BFRT group as compared to conventional rehabilitation control [14]. Similar finding was also reported by Curran et al. (2020) who did not observe significant changes in IKDC scores after BFRT [12]. So, the inconsistencies and heterogeneities in effectiveness of BFRT demonstrate its role certain to function and specific protocol used in clinical trials. The analysis of factors influencing BFRT outcomes were also analyzed below to determine their impact.

Analysis of factors influencing BFRT outcomes

Timing of Intervention

Pre-operative Only: There is limited effectiveness report of BFRT exclusively when it is applied before surgery. Tramer et al. (2023) carried out RCT expanded on a span of 2-week. The authors applied home-based BFRT prehabilitation program to determine effectiveness. There was no significant difference found in quadriceps strength or patient-reported outcomes compared to a standard pre-rehab protocol on the day of surgery [16].

Peri-operative: A more extended application spanning both pre- and post-operative phases may yield early, albeit transient, benefits. The transient nature of the benefit observed by Okoroha et al. (2023), whose protocol spanned 2 weeks pre-op to 12 weeks post-op, implies that while BFRT may accelerate early gains, it does not confer a long-term advantage over standard care in this mixed-timing model [15].

Post-operative (Early to Mid-term): The most consistently positive results are found when BFRT is applied during the post-operative period. De Melo et al. (2022) initiated BFRT in the initial post-operative phase (up to 12 weeks) and reported superior gains in both quadriceps and hamstring strength compared to high-load training [13]. Similarly, Xuefeng Li et al. (2023) applied BFRT in the mid-term phase (starting after 8 weeks) and also found significant improvements in muscle strength and thickness [17]. So, BFRT is showing promising utility in early or mid-post operative duration to prevent surgically induced muscle deficit.

Interaction with Exercise Intensity and Type

With High-Intensity Exercise: BFRT does not play additive or adjunctive role in addition to already high intensity training. Curran et al. (2020) findings indicated that BFRT combined with high-intensity exercise (70% 1RM) resulted in no higher levels of quadriceps strength, activation, and volume compared to high intensity exercise alone [12]. This suggests that increased muscle protein synthesis could already be fully achieved by the high mechanical tension and the additional metabolic toxicity by BFRT does not add any advantage.

With Low-Load Exercise: However, the studies depicting a positive effect have consistently used BFRT in combination with low loaded exercise. De Melo et al. (2022) have found that the BFRT causing training with low load (30% 1RM) is more effective compared to high-load (70% 1RM) BFRT [13]. Another study Xuefeng Li et al. (2023) also combined BFRT with conventional low-intensity rehabilitation program and found it to be very effective [17]. This supports the most proposed mechanism of BFRT: acquisition of gains in similarity to high-load training via utilization of loads, which are less damaging and more tolerable in a post-surgical setting.

BFRT Dosage and Pressure

Although the majority of results utilized a uniform pressure of 80% limb or occlusive arterial pressure (LOP/AOP), the one study directly comparing the different pressures allows us to draw some important conclusions regarding variability in dosage. However, Xuefeng Li et al (2023) in their trial specifically compared 80% AOP, 40% AOP, and no BFR control group. Their results were conclusive: the 80% AOP group exhibited significantly greater strengthening and increase in muscle thickness of quadriceps as compared to both 40% AOP and control groups [17]. Furthermore, the 80% AOP group was also superior to the 40% AOP group on these measures. This result firmly indicates that increased occlusion pressure is more functional and dose-response relationship exists in BFRT usage. To sum up, the effectiveness of BFRT is not an absolute, and it seems to be strongly reliant on how it is used. The evidence is directed to its best potential of application during after-operative riddles, together with low-intensity exercise, and at high pressure (e.g. 80% AOP).

Safety and Tolerability

The most important factor to consider in a new clinical intervention is safely profile and the tolerance by the patients. Even in the case of the introduction of limb occlusion that is not complete, it should be considered carefully to exclude adverse events and patient comfort. The general conclusion in the reviewed included clinical trials was that BFRT was a safe modality, but with tolerability problems observed. The most detailed account of patient tolerability belongs to Okoroha et al. (2023), who reported that three (3) patients (13.6) of 22 patients in the BFRT group (13.6) chose to withdraw of the research because of intolerability and discomfort during the exercise with cuffs, and intolerability to the cuff [15]. This shows that the physical experience of

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compression is not well-tolerated by all patients and as a hindrance to adherence, this may be a barrier to adherence in a proportion of patients despite the intervention itself.

Nonetheless, most of the studies had found a conclusion that their BFRT protocols were safe and manageable. The home-based BFRT prehabilitation protocol developed by Tramer et al. (2023) proved to be feasible, accessible, and tolerable by patients, without any complications encountered [16]. Equally, De Melo et al. (2022) found that no deep vein thrombosis, skin lesions, or hematomas were reported in any patient in the process of their study, despite such effects being reported by the patient, which were mild, short-lived, and cased by cuff deflation [13]. So, BFRT is somehow safe and do not cause critical adverse side effects or events in ACLR group.

Strength and Limitations

There are a lot of strengths of this systematic review. Evidence is synthesized by including recent (last five years) randomized controlled trials, which is rated as high quality evidence. The systematic review was conducted following PRISMA 2020 guidelines. The critical appraisal or methodological quality assessment was carried out using standardized Cochrane ROB 2.0 tool. The literature search was conducted using peer-reviewed and English language articles. However, the evidence overall ROB showed some concerns, emphasizing further validation through multicenter and more robust study designs to validate the findings. There maybe language bias because only English language articles were considered for synthesizing evidence. The overall inconsistency of effectiveness of BFRT was reported in this systematic review due to heterogeneity in methodologies and protocols used among 7 RCTs.

Future Recommendations

Owing to the inconsistencies in overall effectiveness of the BFRT, there is need to consider more refined and consistent methodologies were analyzed in future RCTs to determine the effectiveness of BFRT among ACLR patients. Future researchers are more encouraged to include non-English RCTs to diversify the evidence synthesis. The future researchers are also encouraged to focus on standardized refined methodologies in their RCTs ensuring consistency and focusing only on intended intervention to reduce the D2 Cochrane ROB 2.0 bias. Future more robust multi-center RCTs are emphasized to generalize the findings because all 7 RCTs are single center.

Conclusion

The effectiveness of BFRT in ACLR rehabilitation reported inconsistencies. One suggested model of the BFRT incorporation into the ACLR rehabilitation would be to focus its application during the early post-operative period (e.g. between 2-8 weeks) in combination with the low-load resistance training (e.g. <30% 1RM) and then continue to be implemented at the mid-term period when the high load training (e.g. >70% 1RM) is not tolerated. There is overwhelming support in the fact that 80% or higher AOP/LOP is the maximum dose that should be used to achieve optimal efficacy in increasing muscle strength and size. On the other hand, this model would not support the use of BFRT as an adjunct to the already existing high-intensity protocols to provide better pain relief, or in combination with cross-education training because it does not support the addition of benefit. Hence, it should be used with target and protocol-related clinical applications, which should be exploited by using it as the main tool used to close the severe gap of early-stage recovery to the ability to train high-load strength programs. The overall ROB of evidence showed some concerns, indicating more studies to validate the findings and suggesting caution while interpreting results. More robust multicenter RCTs are emphasized to generalize the findings.

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