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The Effect of Blood Flow Restriction Training on Quadriceps Activity After Anterior Cruciate Ligament Reconstruction: A Preliminary Randomized Controlled Trial

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ABSTRACT

Background: After anterior cruciate ligament reconstruction, a crucial priority is restoring knee muscle strength, especially the quadriceps, to reach the pre-injury strength levels as fast as possible. A feasible alternative to heavy loading might be blood flow restriction training that may elicit quadriceps muscle strength adaptations using low external loads. This study assessed whether quadriceps strengthening using low load blood flow restriction (LL-BFR) would enhance electromyographic (EMG) activity of the vastus medialis (VMO), vastus lateralis (VLO), and rectus femoris (RF) similar to quadriceps strengthening using heavy loads resistance training (HLRT). The secondary objective was to assess intra-quadriceps regional EMG differences between the 3 quadriceps muscle heads.

Methods: Twenty-six patients were recruited after anterior cruciate ligament reconstruction and divided into 2 groups (LL-BFR and HLRT) 3 months after surgery. Patients performed 1 set of 12 repetitions of knee extension during which the EMG activity of the VMO, VLO, and RF was measured with the FREEEMG electromyographic system. The maximal voluntary isometric contraction normalized the EMG results.

Results: On EMG data, significant in-between group differences were found, highlighting a higher activation for the HLRT group ($p = 0.01$), VMO ($p = 0.002$), and VLO ($p = 0.002$), as compared to the LL-BFR group. No significant differences were observed between RF and vasti muscle activation in the LL-BFR group ($p = 0.89$) and HLRT group ($p = 0.12$)

Conclusion: These findings indicate that HLRT may elicit a significant increase in quadriceps EMG activity, an effect not seen in the LL-BFR group

KEYWORDS
blood flow restriction; quadriceps muscle activity; low load; anterior cruciate ligament reconstruction

INTRODUCTION

After anterior cruciate ligament reconstruction (ACLR), the use of blood flow restriction (BFR) optimizes muscle strengthening and reduces joint stress by combining blood occlusion with low loads (LL).[1]

Quadriceps dysfunction is commonly found after ACLR and results in amyotrophy and loss of strength that may last for years. In addition, shortly after surgery, the literature demonstrates that the loss of quadriceps volume and strength results from immobilization associated with neurological inhibition and unloading of the limb.[2] Many factors may cause quadriceps atrophy (inflammation, swelling, joint laxity, pain and loss of sensory receptors, and arthrogenic muscle inhibition). The weakness of this muscle after ACLR is partially due to morphological changes in the muscle. Indeed, from 5 days of non-use, Wall et al. highlight an increase in the expression of myostatin and ubiquitin kinases, both of which are molecules responsible for amyotrophy.[3]

This amyotrophy affects knee function and can delay return to participation and subsequently return to competition. It leads to an asymmetry between the lower limbs associated with impaired articulation and gait mechanics.[4] This abnormal gait may contribute to the development of knee osteoarthritis. The reported between-limb quadriceps strength difference has been reported between 5-18% up to 15 years after surgery.[5] Thus, to optimize recovery and bring the patients back to their pre-rupture functional level, BFR is presented as a transition therapy to high-intensity exercise.

Fujita et al. reported that light strength training combined with BFR increases endurance, phosphorylation, and muscle protein synthesis and promotes increased strength while providing the same gains as muscle-building conventional with high loads.[6] Similarly, Laurentino et al. showed that reducing painful phenomena, such as arthrogenic muscle inhibition, would improve muscle recruitment.[7]

Several studies have reported the acute[8–14] and chronic[15–24] effects of muscle size increases with the BFR. Nevertheless, very few studies have focused on the analysis of EMG muscle activity with the use of LL-BFR and/or with HLRT in patients after ALCR.[25]

The primary objective of this study was to assess whether quadriceps strengthening using LL-BFR improves electromyographic (EMG) activity of the vastus medialis (VMO), vastus lateralis (VLO), and rectus femoris (RF), similar to HLRT. The secondary objective was to assess intra-quadriceps regional EMG differences between the 3 quadriceps muscle heads.

METHODS

STUDY DESIGN

This randomized controlled trial (RCT) was approved by the local ethics committee of the Clinic of Domont (IRBN: PCE- 05.22.135), and participants were recruited from 01/03/2022 to 02/04/2022 via medical consultation referrals. Before participation in the study, all patients provided written informed consent in compliance with the Declaration of Helsinki.

This study has been designed and reported in line with the CONSORT recommendations for reporting randomized trials.[26]

SAMPLE SIZE CALCULATION

The G-power software and previously reported effect sizes were used to calculate the sample size.[27,28] A sample of 16 individuals was determined for an error probability of 0.05, an effect size of 0.8, and a power of 0.90.

PARTICIPANTS

Twenty-seven recreational athletes with an ACLR were evaluated against the inclusion/exclusion criteria, and 26 (9 women) were eligible to participate. Patients were included if:

- they were between 18 and 35 years of age
- they had undergone ACLR with a hamstring autograft
- their ACL injury had occurred during sports participation (regardless of the type or the mechanism)
- they had a body mass index (BMI) < 30 kg.m-2
- their activity level before the ACL injury was a Tegner Activity Level Scale score ≥ 4 and a score on the Marx Activity Rating Scale ≥ 7
- surgery was performed at least 3 months before the assessment.[29,30]

The general exclusion criteria were past or existing ACL injuries of the ipsilateral knee and reconstruction for iterative lesions. Due to the application of BFR training, patients with historical or present cardiovascular disease, high blood pressure (>140/90), venous deficiency, breast surgery, and a history of deep venous thrombosis were also excluded.[31] Patients who underwent meniscal repair and/or meniscectomy were not excluded, but patients with associated lesions other than meniscal were excluded (e.g., osteochondral lesions, multiple ligament lesions).

Eligible patients' baseline information was recorded and included medical data (graft type, date of surgery), demographics (age, body mass, height), and sports participation data (Tegner and Marx scores before anterior cruciate ligament injury).

Randomization and Blinding

Participants were allocated into the LL-BFR and the HLRT groups using a block randomization process (block size of 4) generated using a randomization website (http://www.randomization.com) by an external investigator, who had no contact with participants throughout the trial. Group allocation was concealed for all ACLR participants and the study personnel (outcome assessor and data analyst) throughout the study. Allocations were placed and sealed in consecutively numbered opaque envelopes by a secretary not involved in the recruitment.

Given the nature of the intervention (BFR application), physiotherapists delivering the exercise program and patients could not be blinded to the group allocation.

Determination of Limb Occlusion Pressure

Participants were instructed to remain as stable as possible, and the complete arterial limb occlusion pressure (LOP) was assessed in a seated position.[32–35] The calculation of BFR parameters and the training were carried out using an automatic personalized tourniquet system (Mad-Up Pro, Angers, France). The 10.5 cm-width cuff was placed at the most proximal part of the thigh and kept inflated throughout the exercise session. The LOP for the LL-BFR group was set at 80% of the complete arterial occlusion pressure.

Muscle Maximal Isometric Torque

The patients were seated to evaluate their quadriceps' maximal voluntary isometric contraction (MVIC). Their MVIC was assessed with the knee flexed at 90°. The ankle was secured to a hand-held dynamometer (Hoogan Microfet 2), with the trunk and pelvis held at approximately 90° and secured by straps on the thigh to avoid compensatory movements. Evidence suggests that knee flexion angles greater than 60° minimally load the ACL,[36] allowing a safe testing or intervention post-ACLR. Subjects were then asked to perform three 5-second MVICs with a 60-second rest period in between to avoid muscle fatigue.[37,38] During testing, participants were verbally encouraged to push as hard as possible.

The highest torque achieved over the 3 tests was used as the MVIC, and the highest EMG signal was used for further analysis.

Outcome Measure: Surface Electromyography

VMO, VLO, and RF activation were measured by surface EMG during the MVIC testing using the FREEEMG system (BTS Bioengineering, Milan, Italy). Electrodes were positioned according to the recommendations of surface electromyography for non-invasive muscle assessment (SENIAM)[39] to avoid overlap and cross-talk of the innervation zones and muscles, respectively. The skin of the thigh was shaved, abraded, and cleared with alcohol. Active bipolar electrodes, with a distance of 20 mm between the poles, were placed longitudinally over the VMO, RF, and VLO muscle bellies to record the electrical activity of the quadriceps. Raw EMG signals were treated with a 50-value moving average and normalized according to the MVIC.[40,41]

The EMG Analyzer software (BTS Bioengineering, Milan, Italy) captured and processed force and EMG signals. Centering, smoothing, and moving average data were analyzed using a specific protocol. This protocol allowed analysis of each activity measurement throughout 50 values from the continuous moving average. This processing was carried out for the EMG raw data of each muscle on each test for all participants. Surface EMG signals were captured with the following parameters:

biological amplifier (CMRR > 95 dB), input impedance high (10 MΩ), low noise (<5 µV RMS), 10-490 Hz bandwidth, and 1500x gain.

INTERVENTION

In this single-session intervention, participants were randomized to either an LL-BFR group using 80% complete arterial LOP or an HLRT group without applying BFR.

Initially, all participants performed a 10-minute warm-up on a cycle ergometer at a moderate intensity. Subsequently, the EMG electrodes were positioned to measure the muscle activity and remained attached throughout the intervention. LL-BFR and HLRT groups performed 12 knee extension repetitions (90° to 0°) on a leg extension machine. A metronome was used to pace the performance of the exercise (2-second concentric and 2-second eccentric phase). The metronome and a stopwatch were placed next to the participants to provide auditory and visual feedback.[42] The HLRT group performed the exercise with a load of 80% MVIC without applying BFR (Farup et al., 2015; Hansen et al., 2020; Ratamess et al., 2009),42-44 while the LL-BFR group performed the exercise with a load equal to 30% MVIC and at 80% of complete LOP.[43,45,46]

STATISTICAL ANALYSIS

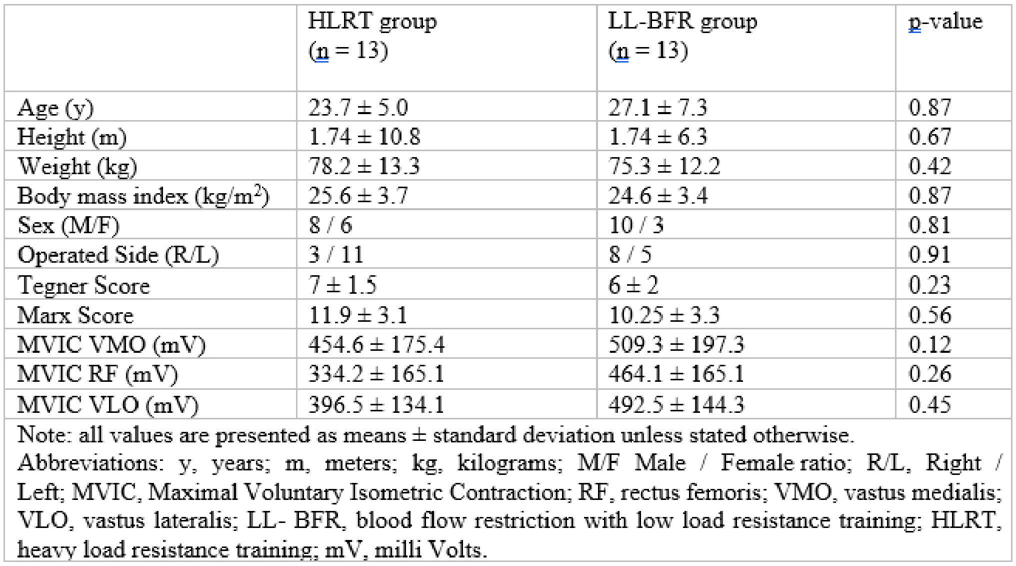
The baseline and demographic characteristics of the participants were summarized and presented. The residuals of each variable were checked for normality by visual inspection of the frequency histograms and the Q-Q plots and tested statistically using the Shapiro-Wilk test.[47] Statistical analysis was performed using Excel ® and Jasp ® software, and the level of significance was set at 0.05. To test the homogeneity of the population, a Pearson Chi-Square test was carried out for the qualitative variables (sex, operated side) and a Mann-Whitney test for the quantitative variables (age, height, weight, body mass, MVIC, and Tegner and Marx scores).

An independent samples t-test was used as a univariate analysis to compare each myoelectric activity between the 2 groups. The effect estimate (effect size) was calculated and reported as Cohen's d (with d = 0.2, 0.5, and 0.8 indicating small, medium, and large effects, respectively).[48]

Finally, a 3-way repeated measures factorial analysis of variance (ANOVA) was used to evaluate any within-group difference in the EMG activity between the 3 muscle heads RF, VMO, and VLO.

RESULTS

Demographic and baseline characteristics
The mean age of the participants was 25.5 ± 6.4 years. Table 1 summarizes baseline data. No statistically significant differences were observed



	HLRT group (n = 13)	LL-BFR group (n = 13)	p-value
Age (y)	23.7 ± 5.0	27.1 ± 7.3	0.87
Height (m)	1.74 ± 10.8	1.74 ± 6.3	0.67
Weight (kg)	78.2 ± 13.3	75.3 ± 12.2	0.42
Body mass index (kg/m^2)	25.6 ± 3.7	24.6 ± 3.4	0.87
Sex (M/F)	8 / 6	10 / 3	0.81
Operated Side (R/L)	3 / 11	8 / 5	0.91
Tegner Score	7 ± 1.5	6 ± 2	0.23
Marx Score	11.9 ± 3.1	10.25 ± 3.3	0.56
MVIC VMO (mV)	454.6 ± 175.4	509.3 ± 197.3	0.12
MVIC RF (mV)	334.2 ± 165.1	464.1 ± 165.1	0.26
MVIC VLO (mV)	396.5 ± 134.1	492.5 ± 144.3	0.45

Note: all values are presented as means ± standard deviation unless stated otherwise.
Abbreviations: y, years; m, meters; kg, kilograms; M/F Male / Female ratio; R/L, Right / Left; MVIC, Maximal Voluntary Isometric Contraction; RF, rectus femoris; VMO, vastus medialis; VLO, vastus lateralis; LL- BFR, blood flow restriction with low load resistance training; HLRT, heavy load resistance training; mV, milli Volts.

TABLE 1. Demographic and Baseline Characteristics

between the 2 groups.

EMG of the HLRT and LL-BFR Groups

Significant between-group differences were found in the mean EMG muscle activation for all the measured muscle heads of the quadriceps muscle (Table 2, Figure 1). These findings indicate a significant increase in the large and very large effect sizes of the EMG muscle activity in favor of the HLRT.

Comparison of the Intra-Muscular EMG Quadriceps Activity

No significant interaction was found for the within-group mean EMG activation of the 3 heads of the quadriceps muscle for the LL-BFR group (F=2.259, p=0.13) and the HLRT group (F=0.115, p=0.89).

	HLRT group (n = 13)	LL-BFR group (n = 13)	p-value	Cohen's d
RF (%MVIC)	50.5 ± 14.6	36.7 ± 17.4	0.018	0.87
VMO (%MVIC)	56.3 ± 19.1	31.1 ± 18.1	0.002	1.26
VLO (%MVIC)	59.8 ± 23.0	29.5 ± 19.1	0.002	1.35

Note: all values are presented as means ± standard deviation.
Abbreviations: MVIC, Maximal Voluntary Isometric Contraction; RF, rectus femoris; VMO, vastus medialis; VLO, vastus lateralis; LL-BFR, blood flow restriction with low load resistance training; HLRT, heavy load resistance training.

TABLE 2. Comparison of EMG Between HLRT and LL-BFR Groups

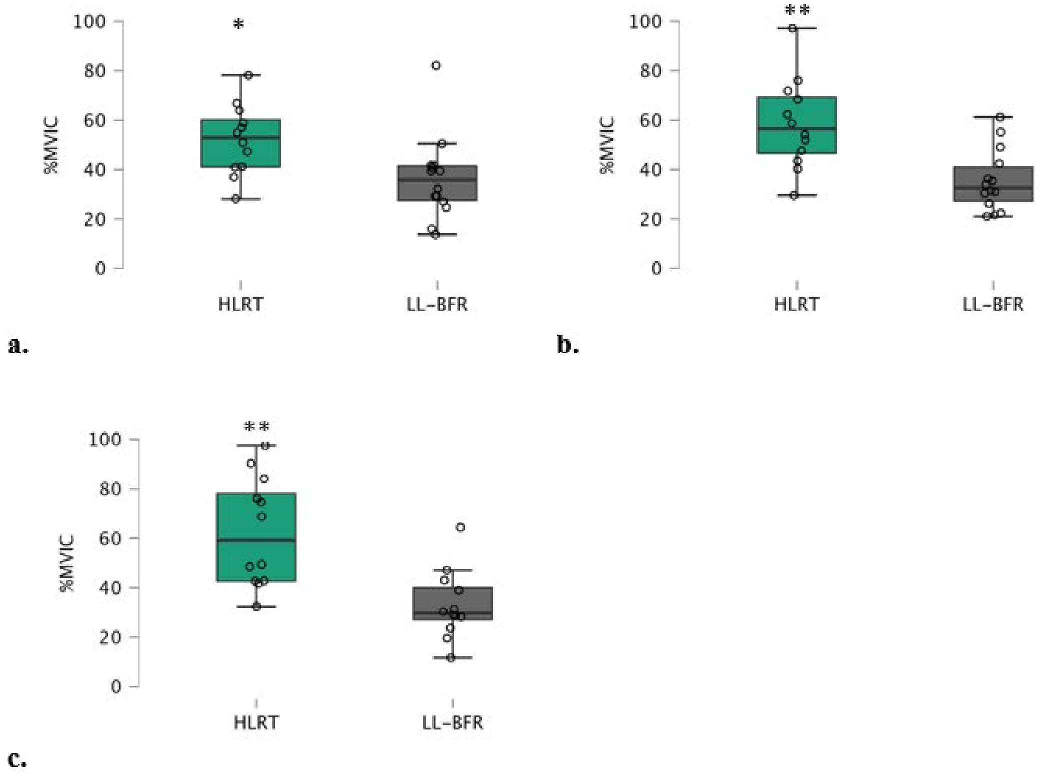


FIGURE 1. Comparison of EMG (a) RF, (b) VMO, and (c) VLO between HLRT and LL-BFR groups
Note: asterisks indicate between-group statistically significant differences (* indicates p<0.05, ** indicates p<0.01).

DISCUSSION

This study demonstrated that a single LL-BFR (30% MVIC) set induced lower quadriceps EMG activity than HLRT (80% MVIC) 3 months after ACLR. No significant differences were observed between the mean EMG of RF, VMO, and VLO in the LL-BFR and HLRT groups, indicating that the training mode does not affect the within-muscle activation.

Following ACLR, the quadriceps EMG activity can be affected by the presence of pain or post-operative muscular inhibition, an observation that may be present even in the long term.[49,50] It has been reported that up to 43% of operated knees present some degree of arthrogenic inhibition and that it would be identified in both limbs in 25.5% of operated patients.[51] Although HLRT seems to elicit better results in strength gains when indicated,[52] LL-BFR has been suggested that might benefit patients after ACLR not only by reducing joint loading in the first stages of rehabilitation but also by increasing central neural drive and cortico-spinal excitability.[53] Limited evidence suggests that the short-term preconditioning with LL-BFR led to significantly increased muscle excitability compared to sham-BFR intervention 4 weeks following ACLR.[25] To the authors' knowledge, most evidence for BFR-driven muscle excitability has been reported in studies of healthy individuals, and no study has yet evaluated the effectiveness of BFR training in the early stages of rehabilitation in reducing athrogenic muscle inhibition. Hence, this should be addressed in future studies.

Similarly to this study's findings, previous research in healthy individuals has linked the training load magnitude with muscle excitability, indicating that HLRT may induce significantly higher EMG activity than LL-BFR in repetition-matched exercises.[54–56] The load magnitude has been suggested to be the only moderator of this effect. HLRT increased muscle excitability compared with LL-BFR regardless of voluntary failure or not—with moderate and high effect sizes, respectively.[54] From a different perspective, adding BFR in low-load resistance training has been reported to increase muscle excitability regardless of whether exercises are performed to volitional failure or non-failure, indicating that BFR may be the driver of these responses.[54] However, it is unclear if such an application in clinical populations could elicit similar neuromuscular responses. The generalizability of this study's results and previous results (in healthy individuals) is limited due to the significant diversity of limb occlusion methods, devices, and parameters, the mode and type of exercise implemented, the plausible cross-training effects, and the possible underloading in this pilot study. Low-load training in non-failure exercises is usually used in early rehabilitation protocols to increase muscle excitability and strength through motor/neural drive adaptations without aggravating pain.[57,58] Nevertheless, these findings are in support of the addition of BFR with low training loads, at least at the initial stages of rehabilitation (long-term training is indicated, not a single session),[54] where higher loads are not recommended or not easily achievable due to pain or other reasons. It has been suggested that muscle recruitment depends on two essential parameters: the percentage of maximum resistance used in loading and the percentage of limb occlusion pressure, which must be constant throughout the exercise.[23,59,60] Standardization of BFR protocols and evaluation of the most effective loading and occlusion parameters are still missing, especially in post-operative management.

The percentage of occlusion pressure in BFR training seems to play an important role in muscle size and strength gains[10,23,24,61,62], pain reduction[63–65], and muscle activation.[66,67] Preliminary evidence shows that LL-BFR (30%RM) produced similar muscle activation to those training with a high load (80%RM).[67] Despite these results, it could be argued that protocol differences, as seen in other studies, may lead to changes in results, specifically on loading protocols using four sets performed to failure instead of a single set.

The relationship between EMG activity and muscle strength is a recurring topic in the literature, but the results remain controversial. Evidence suggests that high loads are required for significant increases in strength and muscle mass, especially for the quadriceps.[52,68] However, strength is not directly proportional to muscle activity.[69] In the present study, the performance of a single set of HLRT elicited higher quadriceps excitability than LL-BFR. Hence, an interesting objective of future studies would be to evaluate if there is a link between the quadriceps EMG and gains in strength and muscle mass.[40]

Limitations

This study cannot exclude that the findings were mainly driven by the single set of exercises utilized, as the total volume of the exercise indicated by contemporary BFR research differs. Given the under-researched field of intermediate-phase ACLR rehabilitation using BFR, a pilot study was much needed. Also, the authors acknowledge that a limitation is the lack of prospective registration of a randomized controlled trial. The authors suggest that an important area of future research is evaluating the electrical activity of the quadriceps muscles in patients with different ACLR graft types and activity levels.

The authors also acknowledge the limitations of using surface EMG during movement and that it is not directly correlated to long-term adaptations in the neuromuscular system. Muscle activity following BFR training might also have been modulated by adaptations in the central motor drive due to subjective exertion, a parameter that was not evaluated in this study.

CONCLUSION

The current results indicate the benefits of heavy load (80%MVIC) in quadriceps recruitment after ACLR. This study agrees with previous literature that tested similar protocols and supports current recommendations that heavy load (80%MVIC) remains the most suitable for quadriceps muscle strengthening after ACLR. These results highlight several perspectives that would be interesting to consider for future research and clinical practice. If BFR associated with the low load (30%MVIC) is effective, the literature shows that its effectiveness in terms of muscle recruitment depends on the device, the LOP, the applied load, fatigue muscle induced, spatiotemporal modalities of contraction, and periodization of training. It would also be interesting in the context of a protocol similar to the present one to measure the constraints on the graft since the combination of an open kinetic chain and a low load at the same level of muscle recruitment, which could constitute a highly important and impactful advance in rehabilitation after ACLR.

INFORMED CONSENT

All patients provided written informed consent in compliance with the Declaration of Helsinki before participation in the study.

CONFLICTS OF INTEREST

The authors declare they have no conflicts of interest.

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