

Case Report

Prehabilitation with Low-Load Blood Flow Restricted Resistance Exercise Training Attenuates Muscle Inhibition of Quadriceps Femoris Muscle in Polytraumatized Patient: A Case Report

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Abstract

Background: Severe knee trauma and chronic cruciate ligament insufficiency are commonly accompanied by marked quadriceps femoris (QF) atrophy and weakness. High-load strengthening is often poorly tolerated by patients with compromised joint stability; therefore, low-load blood flow restriction resistance training (LL-BFRT) may serve as an effective alternative. **Case presentation:** A 38-year-old male presented 27 months after motorcycle-related polytrauma with right knee pain, instability, complete anterior and posterior cruciate ligament ruptures, and partial QF denervation after femoral nerve injury. Before surgery, he completed a supervised 5-week LL-BFRT prehabilitation program (13 sessions). **Results:** Lean thigh circumference increased by 5.9% proximally and 17.7% distally. Voluntary activation increased from 87.2% to 92.5%, and maximal QF EMG median frequency decreased by 7.4%. Knee extensor isometric and concentric (60°/s) peak torque increased by 52.4% and 36.9%, respectively. QF isometric endurance time increased from 48.5 to 61.8 s. Stair-climbing time decreased from 18.9 to 10.6 s, repetitions in the step-down test increased from 10 to 17, and the Y-balance test composite score increased from 77.7% to 99.4%. **Conclusions:** Substantial physiological and clinical improvements in QF voluntary activation, maximal strength, endurance, and lower limb function were observed following a short-term LL-BFRT program in a patient with multiple ligament injuries. Changes in lean thigh circumference were consistent with possible improvements in muscle size; however, muscle hypertrophy was not directly assessed.

Keywords: ischaemic training; voluntary muscle activation; polytrauma; knee; musculoskeletal injuries



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1. Introduction

Quadriceps femoris (QF) muscle dysfunction following knee ligament injury or reconstruction is caused not only by atrophy or disuse but also by changes in neural drive, resulting in the phenomenon of arthrogenic muscle inhibition (AMI). This is characterized by altered muscle activation around an injured joint, arising from factors such as pain, swelling, inflammation, and deafferentation, and is widely considered to contribute to QF strength loss and atrophy after anterior cruciate ligament (ACL) injury or reconstruction [1,2]. In a recent methodological analysis of QF weakness in individuals with ACL reconstruction, central activation failure was highlighted as a key factor contributing to this weakness [3,4]. From a broader neuromuscular perspective, maximal muscle force

depends on optimal activation and transmission across both central and peripheral pathways. Reductions in force may result from disruption at the central level (such as impaired corticospinal drive) or at the peripheral level (such as neuromuscular junction, muscle membrane excitability, or peripheral nerve compromise) [2,5]. In clinical cases of polytrauma patients where injuries of passive joint structures co-exist with muscle and nerve injuries, a complex interaction of muscle atrophy, peripheral denervation/reinnervation, and central activation failure driven by AMI limits full recovery of skeletal muscle function and exacerbates disuse atrophy by reducing the effectiveness of therapeutic exercises.

Physiotherapy prior to joint reconstruction surgery, i.e., prehabilitation, aims to optimize QF neuromuscular function, reduce pain and effusion, and improve readiness for surgery. Studies indicate that greater preoperative QF strength deficits are independently associated with poorer subjective knee function one year after ACL reconstruction [6], while prehabilitation with exercise training applied before surgery has been shown to attenuate postoperative QF muscle atrophy [7], further supporting the importance of optimizing neuromuscular status prior to ligament reconstruction. Although standard strength training paradigms typically recommend moderate-to-high external loads to induce neural and morphological neuromuscular adaptations, such intensities are often not feasible following ligament injury and polytrauma due to provocation of joint pain, effusion, instability, and potential reinjury [8].

Low-load blood flow restriction resistance exercise training (LL-BFRT) is a clinically relevant strategy to address the challenge of achieving sufficient neuromuscular stimulus while minimizing mechanical stress. By partially restricting limb blood flow during low-intensity resistance exercise (typically 20–40% 1RM), LL-BFRT creates a hypoxic, metabolite-rich intramuscular environment that can promote fatigue of oxidative muscle fibres and hence earlier recruitment of higher-threshold motor units despite low external loads [9–11]. Evidence indicates that LL-BFRT can induce strength, hypertrophy, and neuromuscular adaptations comparable to traditional high-load training without increasing the risk of joint reinjury when appropriately applied [10,12,13]. Although studies report improvements in QF strength, muscle activation, and functional outcomes with LL-BFRT in patients with ACL injuries [12,14,15], patients with multiple ligament injuries and concomitant neurological impairment are typically excluded from clinical trials. Consequently, evidence guiding the use of LL-BFRT in preoperative rehabilitation of polytraumatized patients with combined ACL and posterior cruciate ligament (PCL) rupture with impaired neuromuscular drive is absent.

The aim of this case report is to examine the safety and effectiveness of a 5-week LL-BFRT prehabilitation protocol applied to a patient with a complete rupture of the ACL and PCL and partial QF denervation prior to scheduled reconstructive surgery of the right knee.

2. Materials and Methods

2.1. Case Description

This case report was prepared in accordance with the CARE checklist [16]. Written informed consent was obtained from the patient for publication of this case report and any accompanying images.

The patient was a 38-year-old man (72 kg, 187 cm) who presented for preoperative assessment and rehabilitation 27 months after a high-energy motorcycle collision. The initial trauma caused severe polytrauma involving the thorax, spine, and multiple structures of both lower limbs and was further complicated by acute multi-organ failure during the acute phase. After medical stabilization and recovery, he reported persistent right knee dysfunction characterized by recurrent instability episodes, pain, intermittent swelling, activity limitations, reduced functional capacity, and decreased knee range of motion. Immediately

after the accident, there was partial right QF denervation due to femoral nerve injury and complete denervation of the gastrocnemius, peroneus longus, and tibialis anterior muscles due to bilateral sacral plexus injury. At the last electrophysiological examination, performed 22 months after the accident, the conduction velocities of the motor fibres of the right femoral nerve and compound muscle action potential of QF were only mildly reduced ($\leq 10\%$), and there was marked improvement in the motor conduction velocities of both tibial nerves, whereas the sural nerves did not show reliable signs of improvement. The available electrophysiological findings suggested substantial neurological recovery compared with the acute post-traumatic phase. However, residual impairment of the right femoral nerve remained present, accompanied by persistent weakness and atrophy of the quadriceps femoris muscle. In addition, the patient continued to demonstrate bilateral distal lower-limb neurological deficits, manifested clinically by persistent foot drop, more pronounced on the right side. No repeat neurophysiological assessment was performed immediately before or after the LL-BFRT intervention; therefore, the extent of ongoing reinnervation during the intervention period could not be determined.

Clinical examination prior to initiation of LL-BFRT revealed marked atrophy of all main muscle groups of both lower limbs, more pronounced on the right. The patient had difficulty walking due to substantial instability of the right knee joint, weakness of all major knee and ankle muscles, and bilateral foot drop, more pronounced on the right. On examination of the right knee, the Lachman and anterior drawer tests were positive, consistent with ACL deficiency [17]. A posterior sag sign was present, and both the lateral-anterior drawer test and posterior drawer test were positive, indicating PCL deficiency [18,19]. This was consistent with the latest magnetic resonance imaging, which confirmed complete rupture of the ACL and PCL, without associated meniscal injury or osseous lesions. Considering the patient's age, current functional status, and combined cruciate ligament insufficiency, the treating orthopaedic surgeon planned a single-stage ACL and PCL reconstruction using autologous grafts (semitendinosus–gracilis tendons for ACL reconstruction and QF tendon for PCL reconstruction).

The planned intervention with LL-BFRT was therefore focused primarily on strengthening the knee muscles and improving neuromuscular control of the right knee prior to surgery.

2.2. Intervention and Rehabilitation Protocol

The prehabilitation LL-BFRT program was delivered over five weeks. Three sessions per week were scheduled, and the patient completed a total of 13 supervised sessions. The training load was set as the maximum mechanical resistance the patient could overcome for 30 repetitions (30-repetition maximum; 30RM), corresponding to low-load resistance exercise (approximately 20–40% of 1RM). Each supervised session consisted of bilateral leg press, unilateral knee extension, asymmetrical squat, and step-up exercises. All training sessions were supervised by the same physiotherapist to ensure consistency in exercise execution, blood flow restriction application, and progression throughout the intervention period. Additionally, safety and tolerability were assessed clinically during the supervised sessions through routine observation by the treating physiotherapist and patient self-report.

During all exercises, blood flow restriction was applied using an asymmetric pneumatic cuff (University of Ljubljana and Iskra Medical d.o.o., Slovenia) positioned at the proximal thigh, as previously described by Ipavec et al. [20]. The asymmetric pneumatic cuff was applied by the same investigator during all training sessions to ensure consistent cuff placement and blood flow restriction application throughout the intervention period. Cuff pressure was regulated using a pneumatic blood-flow restriction system (Ischemic Trainer, University of Ljubljana and Iskra Medical d.o.o., Slovenia), and it was adjusted in-

dividually for the participant as previously described by Ipavec [21]. After a brief warm-up (10–12 repetitions at minimal workload), the cuff was inflated to an absolute pressure of 130 mmHg and maintained for 30 s at rest before commencing the working sets.

Each exercise was performed for four sets using the same external load, following a decreasing repetition scheme (20, 15, 15, and 10 repetitions). Rest intervals were standardized as follows: 30 s between sets 1–2 and 3–4, with the cuff kept inflated (no reperfusion; cuff ON), and a 45 s reperfusion period between sets 2–3 with the cuff deflated (cuff OFF) (Figure 1). Similar LL-BFRT training protocols have been used in previous studies [22–24]. The patient was instructed not to modify his usual daily activities during the intervention period.

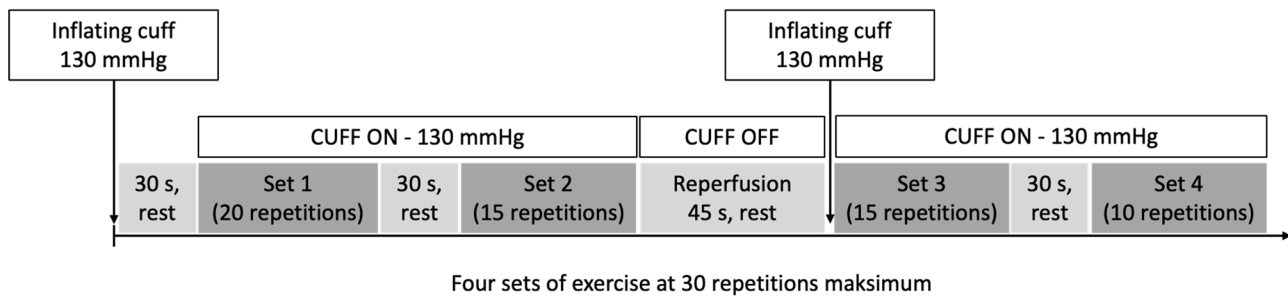


Figure 1. A schematic representation of a single training session with LL-BFRT resistance exercises for knee extensors.

2.3. Tests and Measurements

Thigh circumference and anterior skinfold thickness were measured at 1/3 (proximal) and 2/3 (distal) of the distance between the greater trochanter and the lateral knee joint space using a measuring tape and a digital calliper (Skyndex, Caldwell, Justis & Co., Fayetteville, AR, USA), respectively. All anthropometric measurements were taken by the same experienced physiotherapist. Three measurements were obtained at each site for both thigh circumference and skinfold thickness, and the mean value was used for subsequent analysis. Lean thigh circumference was calculated at both sites according to Lee et al. [25]:

$$\text{Lean thigh circumference} = \text{thigh circumference} - \pi \times \text{skinfold}$$

Neuromuscular performance was assessed immediately before (PRE) and after (POST) the 5-week preoperative LL-BFRT program. Unilateral laboratory-based measurements included (i) MVIC torque of the QF and hamstrings; (ii) QF voluntary activation assessed during MVIC using supramaximal percutaneous femoral nerve stimulation (interpolated twitch technique, expressed as % voluntary activation); (iii) surface EMG median frequency of QF; (iv) maximal concentric peak torque of the knee extensors and flexors during isokinetic dynamometry; and (v) QF isometric endurance during a sustained submaximal contraction at 60% MVIC. A 5 min passive rest period was provided between the first three tests, while a 20 min rest period was provided before the final (endurance) test.

Functional performance was assessed at PRE and POST using three lower-limb tests: the Y-Balance Test (YBT; anterior, posteromedial, and posterolateral reach directions); a 30 s step-down test (number of controlled repetitions from a standard step); and a stair-climbing test (time to ascend and descend a standard flight of stairs). The inclusion of balance and step-based tasks aligns with functional outcome batteries used in blood flow restriction rehabilitation research, including ACL reconstruction cohorts where YBT outcomes are commonly reported, and broader musculoskeletal or knee rehabilitation studies where stair-climbing test outcomes were used to quantify task-specific functional capacity [26–28].

Muscle strength testing

All strength and endurance measurements were performed using an isokinetic dynamometer (Humac NORM, CSMI, Stoughton, MA, USA). A standard gravity correction procedure was applied to all tests. The patient was seated and secured with straps across the trunk and pelvis to minimize compensatory movement. The dynamometer axis was aligned with the lateral femoral condyle, and the tested leg was fixed to the lever arm, with the shank strap positioned just proximal to the malleolar line. The knee joint angle was set at 60° from extension, and the ankle and thigh were strapped to minimize movement [29,30]. The same knee angle was used for the interpolated twitch technique, EMG median-frequency analysis during knee extensor MVIC, and the QF isometric endurance test. The untested limb was stabilized on a support under the chair.

Maximal voluntary isometric contraction (MVIC)

The MVIC protocol began with a standardized warm-up consisting of three submaximal isometric contractions (3–5 s each), performed progressively at approximately 25%, 50%, and 75% of the patient's perceived maximal effort. After a brief rest period, the patient performed three MVIC trials (3–5 s each) for knee extensors, and a similar procedure was used for isometric knee flexor MVIC testing. During all MVIC trials, the patient kept their arms crossed over the chest and received strong verbal encouragement to promote maximal effort. A 30 s rest interval was provided between MVIC trials. The highest torque averaged over 1 s obtained across the three trials was recorded as the MVIC value.

Maximal concentric peak torque

Maximal concentric peak torque of the knee extensors and flexors was assessed during isokinetic testing from 10° to 90° of knee flexion at an angular velocity of 60°/s. The protocol included a warm-up set of 10 submaximal concentric repetitions at progressively increasing ratings of perceived effort (approx. 50–90%). After a 2 min rest period, the patient performed 10 consecutive maximal concentric contractions for the tested muscle group, with strong verbal encouragement provided throughout. Peak torque was defined as the maximal value achieved across the 10 repetitions.

Isometric endurance (QF)

QF isometric endurance was assessed in the same position as isometric strength testing. The target torque was set at 60% of the previously measured MVIC. Real-time visual feedback was provided via a monitor placed in front of the patient, displaying a target line (60% MVIC) and a lower threshold line at 40% of the target value. The test ended at volitional failure or when torque dropped below the termination threshold for more than 3 s despite strong verbal encouragement. Endurance performance was quantified as the time (seconds) for which the target contraction could be sustained.

Voluntary activation (QF) and femoral nerve stimulation

Voluntary activation of the QF was quantified using the interpolated twitch technique. Supramaximal percutaneous femoral nerve stimulation was applied during the torque plateau of each knee extensor MVIC (typically 3–4 s after contraction onset) to evoke a superimposed twitch response. Immediately after the third MVIC, the patient was instructed to relax completely. Three seconds after relaxation, the femoral nerve was stimulated three times at 3 s intervals to elicit potentiated resting QF twitch responses (Figure 2).

Femoral nerve stimulation was administered using a constant-current stimulator (Digitimer DS7AH, Welwyn Garden City, Hertfordshire, UK) with 1 ms square-wave pulses (maximum voltage 400 V). A 12 mm self-adhesive cathode (Red Dot 2560, 3M, Maplewood,

MN, USA) was positioned within the femoral triangle (3–5 cm inferior to the inguinal ligament) and applied consistently by the same investigator. A large anode (7.5 × 13 cm; Axelgaard Manufacturing Co., Ltd., Fallbrook, CA, USA) was placed over the greater trochanter [4].

After familiarization, stimulus intensity was increased in 25 mA increments (3–5 s between stimuli) until twitch torque reached a clear plateau and then increased by a further 20% to ensure supramaximal stimulation (typically 200–500 mA) [4,29–31].

Supramaximal paired stimuli were subsequently delivered during the torque plateau of each MVIC and again at rest 3–5 s post-MVIC to obtain potentiated responses [29,30]. Voluntary activation was calculated as follows:

$$\%VA = [1 - (\text{superimposed twitch torque} / \text{potentiated twitch torque})] \times 100$$

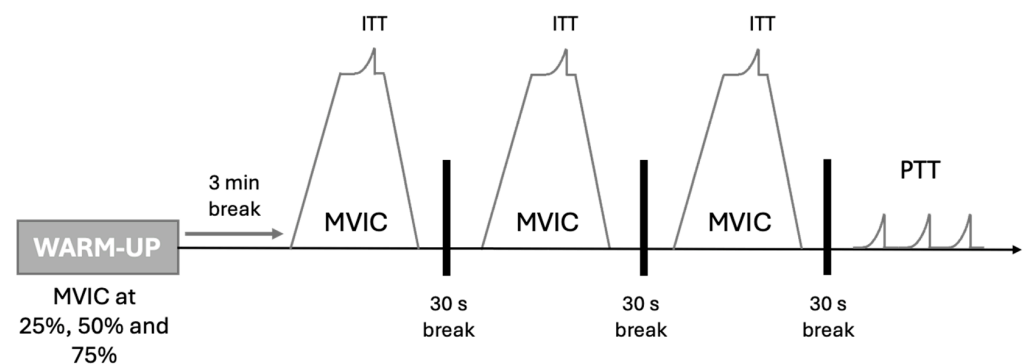


Figure 2. Protocol for measuring peak knee extension torque and level of voluntary muscle activation using the interpolated twitch technique during MVIC and subsequent rest period. Abbreviations: ITT—interpolated twitch technique; PTT—potentiated twitch technique; MVIC—maximal voluntary isometric contraction.

EMG median frequency

Surface electromyography (EMG) of the vastus lateralis and vastus medialis was performed according to SENIAM recommendations [32]. Skin preparation included shaving, light abrasion, and cleaning to reduce impedance (<5 kΩ). Bipolar Ag-AgCl electrodes (Red Dot 2560, 3M, Maplewood, MN, USA) were placed longitudinally over the muscle belly with a 20 mm inter-electrode distance. EMG signals were sampled at 1000 Hz (TEL 1000C and MP150WS, Biopac Systems, Goleta, CA, USA), with a bandwidth of 1–500 Hz and input impedance of 2 MΩ. Raw EMG signals were high-pass filtered at 20 Hz using a digital infinite impulse response filter. Frequency-domain analysis was performed using fast Fourier transform, and the median frequency was extracted as the primary value. Values were averaged across the vastus lateralis and vastus medialis to obtain a composite QF median frequency for analysis.

3. Results

Outcome assessments were completed at baseline (PRE) and immediately after the 5-week preoperative LL-BFRT program (POST). Values are reported for the involved limb (right) unless otherwise stated. No adverse events were observed by the supervising physiotherapist, and the patient did not report new or worsening knee pain, swelling/effusion, discomfort, instability symptoms, or other transient adverse responses during the intervention period. However, no formal adverse-event monitoring protocol was implemented.

3.1. Lean Thigh Circumference

Lean thigh circumference increased from 49.5 cm to 52.4 cm (+5.9%) proximally and from 37.8 cm to 44.5 cm (+17.7%) distally.

3.2. Muscle Strength and Activation

MVIC peak torque increased by 52.4% for the knee extensors and 26.7% for the knee flexors. During isokinetic concentric testing at 60°/s, peak torque increased by 36.9% for the knee extensors and 13.2% for the knee flexors. In the isometric endurance test at 60% MVIC, the time sustained at the target increased by 27.5% (Table 1). QF voluntary activation level increased by 5.3 percentage points, from 87.2% to 92.5%. Average EMG median frequency (v. lateralis and v. medialis muscle) during MVIC decreased by 7.4%, from 63.2 Hz to 58.5 Hz.

Table 1. Changes in peak isometric and isokinetic (60°/s) torques following a 5-week LL-BFRT prehabilitation program (involved limb).

Measurements	PRE	POST	Δ (POST–PRE)	% Change vs. PRE
MVIC knee extensors (Nm)	145	221	76	52.4%
MVIC knee extensors (%BW)	203	307	104	51.2%
MVIC knee flexors (Nm)	60	76	16	26.7%
MVIC knee flexors (%BW)	83	104	21	25.3%
Isokinetic concentric 60°/s knee extensors (Nm)	103	141	38	36.9%
Isokinetic concentric 60°/s knee extensors (%BW)	143	197	54	37.8%
Isokinetic concentric 60°/s knee flexors (Nm)	53	60	7	13.2%
Isokinetic concentric 60°/s knee flexors (%BW)	75	83	8	10.7%

Abbreviations: MVIC—maximal voluntary isometric contraction; %BW—percent body weight; PRE—baseline; POST—post-intervention.

3.3. Functional Performance Tests

Stair-climbing performance improved substantially. Ascent time decreased from 8.40 s to 5.70 s (−2.70 s, 32.1% faster), descent time decreased from 10.50 s to 4.86 s (53.7% faster), and total stair-climbing time decreased from 18.90 s to 10.56 s (44.1% faster). In the 30 s step-down test, repetitions increased from 10 to 17 on the involved limb (+70.0%) and from 9 to 15 on the contralateral limb (+66.7%), with total repetitions increasing from 19 to 32 (+68.4%). In the YBT, the largest improvements were observed in the posteromedial and posterolateral reach directions, particularly on the involved limb (Table 2). The involved-limb composite score increased from 77.7% to 99.4% (+21.7 percentage points), while the contralateral composite score increased from 77.0% to 84.7% (+7.7 percentage points).

Table 2. Y-Balance test directional reach (cm) and composite scores normalized to leg length (%).

Direction	Limb	PRE	POST	Δ (POST–PRE)
Anterior (cm)	Right leg	71.9	77.1	+5.2 cm
	Left leg	80.9	76.3	−4.6 cm
Posteromedial (cm)	Right leg	69.8	99.7	+29.8 cm
	Left leg	55.8	70.4	+14.6 cm
Posterolateral (cm)	Right leg	79.8	106.5	+26.7 cm
	Left leg	79.3	90.8	+11.4 cm
Composite score (%)	Right leg	77.7%	99.4%	+21.7 pp
	Left leg	77%	84.7%	+7.7 pp

Abbreviation: pp, percentage points.

4. Discussion

This case report shows that a 5-week LL-BFRT program conducted in a highly complex patient with a combined cruciate ligament rupture and reported partial QF and lower leg muscle denervation was associated with substantial improvements in thigh muscle strength, functional performance, and voluntary activation. No adverse events were observed or reported during the intervention period. This clinical scenario differs from most controlled rehabilitation trials of LL-BFRT after ligament reconstruction, which typically exclude patients with multiple ligament injuries and/or central or peripheral neurological impairment, thereby extending the clinical plausibility of LL-BFRT to a population with markedly limited loading tolerance and neuromuscular function.

Substantial improvements were observed in functional outcomes, indicating increased capacity for weight-bearing and controlled knee loading. These findings are consistent with the mainly positive effects of LL-BFRT on self-reported function [26,33] and dynamic balance [9,26,33–35] reported in patients with ACL reconstruction. The concurrent improvement across multiple functional tasks in the present case suggests a meaningful enhancement in overall task execution and limb control. This is particularly relevant given the patient's combined ligament instability, severe atrophy, and muscle denervation of both thigh and lower leg muscles. The ongoing muscle reinnervation process in the lower leg may have substantially enhanced strength and neuromuscular control during functional activities, particularly stair climbing and the YBT, but the extent of its contribution remains unknown and therefore hypothetical. Functional endurance measures, such as sit-to-stand and heel-raise performance, have also been shown to improve with LL-BFRT [36]. Previous studies suggest that LL-BFRT may accelerate functional recovery during early rehabilitation after ACL reconstruction, although differences from standard rehabilitation tend to diminish over time [34,35,37]. However, our case suggests that LL-BFRT may also be a feasible and potentially effective treatment option for patients with persistent muscle weakness, even 27 months after the initial polytrauma.

Marked improvements were observed in both knee extensor and flexor strength, with particularly large gains in isometric knee extensor torque. The magnitude of improvement in extensor MVIC torque (+52.4%) and isokinetic peak extensor torque (+36.9%) exceeded that typically reported in ACL reconstruction populations treated with LL-BFRT [12,38]. Previous studies generally report improvements in quadriceps strength comparable to traditional high-load training, although findings remain heterogeneous and should be interpreted with caution [38–42]. Our findings also support previous reports that isometric strength improvements with LL-BFRT are more consistent than isokinetic results [43,44]. Given the importance of quadriceps strength for knee function, the observed increases in extensor and flexor torque are clinically relevant. The fact that the increase in knee flexor muscle strength was half that of the extensors confirms findings from other studies that the effect of LL-BFRT on the hamstring muscles is smaller than on the quadriceps muscles, where attenuation of flexor strength loss or only modest increases in flexor torque have been reported [9,26,45].

The parallel improvements in submaximal isometric endurance (~27%) are noteworthy. Although endurance is rarely assessed in LL-BFRT studies, available evidence suggests that it may preserve or improve muscle endurance in patients with ACL rupture or reconstruction [7,43,44,46], particularly during early recovery after knee surgery. Given the importance of sustained force production for daily activities, these findings suggest that LL-BFRT may enhance not only maximal strength but also fatigue resistance and overall muscle performance.

From a mechanistic perspective, the relatively modest increase in QF muscle voluntary activation level suggests that improvements in central motor drive explain only part of the observed strength gains. At baseline, voluntary activation was below values typically re-

ported in healthy individuals (~92–95%), which is consistent with the presence of AMI [29]. Although activation level increased and approached the normal range after the LL-BFRT program (92.2%), the relatively small change (5.3 percentage points) appears insufficient to fully account for the substantially larger improvements in QF muscle strength (~40–50%) and endurance. This suggests that additional factors, including muscular adaptations, may also have contributed to the observed improvements. The observed increase in thigh circumference (+18% distally) is consistent with possible increases in muscle size, which have been reported following LL-BFRT [46,47]. However, because muscle size was estimated indirectly from anthropometric measurements rather than imaging-based methods, these findings should be interpreted only as suggestive of increased muscle size and not as direct evidence of physiological muscle hypertrophy. Other factors affecting lean thigh circumference, including changes in local tissue hydration, resting muscle tone, or measurement variability, cannot be excluded. Consequently, the present data do not allow for definitive confirmation of physiological muscle hypertrophy. The 7.4% reduction in EMG median frequency during MVIC may reflect changes in neuromuscular function following strength training. However, the specific underlying mechanisms cannot be determined from the present data, as EMG median frequency can also be influenced by multiple physiological and methodological factors, including muscle fibre conduction velocity, motor unit recruitment patterns, synchronization, and tissue properties. Additionally, because EMG median frequency is only an indirect marker, no firm conclusions can be drawn regarding the extent to which reinnervation contributed to the observed strength gains [29]. Together, these may be consistent with contributions from both neural and muscular factors to the observed improvements in muscle performance. However, the present measurements do not allow direct quantification of the relative contribution of individual mechanisms, so any mechanistic interpretation should be considered exploratory.

Clinically, LL-BFRT is a feasible and potentially effective low-load strengthening strategy when high-load resistance exercise is poorly tolerated. No adverse events were observed or reported during the intervention period, which is consistent with the generally favourable safety profile of LL-BFRT reported in previous studies when appropriately applied [10,15]. However, because no formal adverse-event monitoring protocol was implemented, conclusions regarding safety should be interpreted cautiously.

Nevertheless, several limitations must be considered. As a single-case report without a comparator intervention, causal inference is limited, and the observed improvements may partly reflect general training effects, familiarization, motivational factors, normal test-retest variability, or natural recovery. Although the patient was 27 months post-trauma, the potential contribution of continued neurological recovery cannot be completely excluded. The relative contributions of central and peripheral mechanisms cannot be definitively determined from the available measures. While voluntary activation, lean thigh circumference measurements, and EMG parameters provide useful insights, they do not allow precise quantification of the underlying physiological processes. Similarly, the observed increase in lean thigh circumference does not provide direct evidence of muscle hypertrophy because muscle morphology was not assessed using imaging-based techniques. The substantial improvements observed in functional performance measures should be interpreted with caution. In addition to physiological adaptation, functional tests may be influenced by familiarization, learning effects, motivation, and normal test-retest variability. Because only a single baseline and post-intervention assessment was performed and no comparator condition was available, the magnitude of the intervention effect cannot be determined with certainty, although the findings suggest meaningful functional improvement. Another limitation is the limited neurophysiological characterization of the affected limb. The extent of initial knee and ankle skeletal muscle denervation was

evaluated using a five-month-old electrophysiological examination report from the patient's medical history, and no electrophysiological assessment was performed immediately before or after the LL-BFRT intervention. The role of muscle reinnervation in the muscle strength and functional improvements observed in this patient must therefore be considered hypothetical and exploratory. Although the available electrophysiological findings indicated substantial recovery of femoral and tibial nerve function compared with the acute post-traumatic phase, residual neurological impairment remained present and may have influenced both baseline performance and responsiveness to training. Future research should examine LL-BFRT in larger cohorts of patients with multi-ligament injury and associated neurological impairment.

5. Conclusions

After five weeks of supervised LL-BFRT, this patient demonstrated improvements in QF voluntary activation, knee extensor and flexor strength, submaximal muscle endurance, and functional task performance, with no adverse events reported. Although interpretation is limited by the single-case design and absence of a comparator intervention, these findings support the clinical feasibility of LL-BFRT and suggest potential effectiveness as a strengthening approach for patients with complex knee instability and concomitant neuromuscular impairment.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the patient to publish this paper.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

QF	Quadriceps femoris
LL-BFRT	Low-load blood flow restriction resistance training
AMI	Arthrogenic muscle inhibition
ACL	Anterior cruciate ligament
PCL	Posterior cruciate ligament
30RM	30-repetition maximum
MVIC	Maximal voluntary isometric contraction
EMG	Surface electromyography

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