**Title**

**Blood Flow Restriction (BFR) in ACL reconstruction rehabilitation. A randomised controlled pilot study looking at BFR effect on quadriceps and hamstring strength in the first 6 months following ACL reconstruction surgery.**

**Investigators**

Jonathan Mulford 1,2,6

Laurent Willemot 1,6

Zach Young 5

Nathan Pitchford 3

Andrew Williams 3

Ambrose Moore 6

Iain Robertson 4, 6

**Affiliations**

1. Launceston General Hospital
2. Tamar Valley Orthopaedics
3. School of Health Sciences, University of Tasmania
4. Clifford Craig Foundation
5. Achieve Sports Physiotherapy and Rehabilitation
6. Tasmanian School of Medicine, University of Tasmania

**Corresponding Author**

Mulford

**Study Group:**

Surgeons:

Jonathan Mulford, Peter Moore, Tim Marshall, Scott Taylor, Peter Van Winden, David Penn.

Physiotherapy Practices:

ASPR, PhysioTas, InBalance, Physiofit.

**Study Location:** Northern Tasmania

**Contents**

Investigators

Affiliations

Corresponding Author

Study Group

Study Location

1. **Introduction**
2. **Justification for the trial**
3. **Aims**
4. **Methods and analysis**

4.1 Study Design

4.2 Blood Flow Restriction Group

4.3 Control Group

4.4 Physiotherapy guidelines

4.5 Measurement Muscle Strength

**5. Patient Criteria**

**5.1 Inclusion criteria**

**5.2 Exclusion criteria**

**6. Allocation**

**7. Outcomes**

**8. Primary Outcomes**

**9. Secondary Outcomes**

**10. Data Collection**

**10.1Patient Characteristics and Peri-operative Data**

**10.2 Independent data collection**

**11. Trial Flow**

**13. Risks of BFR**

**14. Statistical Methods**

**15. Funding**

**16. References**

**1 Introduction**

The incidence of anterior cruciate ligament reconstruction (ACLR) has dramatically increased over the last few decades 1 possibly due to the increasing high-level athletic participation in the general population 2, 3. Despite ACLR being one of the most frequently performed surgical interventions, ACLR rehabilitation still has controversies 4. Postoperative loss of quadriceps muscle volume and strength, which is almost universally observed after ACLR, is believed to be related to the trauma of the initial injury and surgical intervention and decreased activity associated with the postoperative restrictions put in place to allow graft healing and incorporation 5. This loss of muscle frequently tends to persist long after the end of formal rehabilitation protocols 6, which may result in long-term issues such as decreased performance, lower patient satisfaction, biomechanical imbalance, and a higher risk of recurrent ACL injury 7.

Following injury and ACL reconstruction ongoing thigh muscle weakness and atrophy can strongly affect an athletes chances of returning to sport 8-12. Return to sport protocols usually require good quadriceps strength to close to the contralateral limb in an attempt to avoid reinjury 5, 13. Hence those involved in rehabilitation of patients recovering from ACL reconstructive surgery are trying to find treatments early in the postoperative phase that increase muscle strength and hypertrophy.

The use of hypertrophy training to assist in recovering muscle loss through exercise requires the use of loads surpassing 60% of one-repetition maximum 14. These loads cannot be achieved in the early postoperative phase following ACL surgery due to discomfort after surgery and time required to protect the new ACL graft. Blood Flow Restriction (BFR) training is gaining popularity in rehabilitation of knee injuries as it has shown that by moderate reduction of blood flow to the limb (Blood Flow Restriction (BFR)), muscular growth can be achieved with significantly lower levels of resistance training and joint loading (Takarada et al., 2000)15.This would theoretically allow the patients rehabilitating from ACLR to start low-load resistance in the early post-operative phase without jeopardising the healing of the reconstructed ACL graft.

The mechanism behind blood flow restriction is believed to be due to the creation of an anaerobic environment that causes muscle hypertrophy through cell signalling from anabolic growth factors, increased fast-twitch muscle fibre recruitment, and changes in the rapamycin and myostatin synthesis pathways 16-21.

Previous studies have shown BFR is safe 22 and with limited data potentially can improve muscle strength for patients with weakness related to knee pathology and surgery 23-27. BFR training is not utilised in main stream physiotherapy rehabilitation practices however it’s beginning to be adopted based off the theoretical benefits and on the basis small number of heterogeneous studies 28.

2 **Justification for the trial**

Early clinical results suggested the use BFR in athletes results in quadriceps hypertrophy and increased strength 16, 29, 30. This resulted in the use of BFR in the rehabilitation setting without good clinical studies 28. While some have suggested improvements outcomes 23-27, 31 there has not been consistent studies showing BFR is superior to standard rehabilitation 32. Some have shown a longer time to return to sport 33. Some have shown no difference in quadriceps volume, strength or patient reported outcomes 34, 35.Others have shown BFR has not increased quadriceps strength 36-38 but has improved other patient reported outcomes 37

Systematic reviews have concluded previous studies have methodological flaws and the limited data results in a lack of consensus on recommending BFR training in routine post operative ACL rehabilitation 9, 22, 25, 29, 30, 32, 39. Sham cuffs have rarely been utilised 35, 40, 41. Strength measurements when made are usually done with hand held dynameters that have potential for error. Randomised controlled trials with standardised practical intervention protocols and outcome measurements are required to prove the theoretical benefits and clinical value of BFR training following ACL reconstruction39. These trials will assist in determining if BFR training can be routinely recommended in rehabilitation of ACL patents 42.

In this pilot study we plan to include a sham cuff group, practical use of BFR training in the ACL reconstruction rehabilitation phase, blinding of the patient and strength assessor to randomisation group and the use of a Humac isokinetic dynamometer.

The adoption of BRF in the post-operative rehabilitation protocols could constitute a low-tech addition to standard care with potential improvements in retainment of muscle volume and strength, range of motion and pain reduction, without compromising ACL reconstruction ingrowth and knee stability.

**3 Aims**

The primary aim of this study is to evaluate if the use of BFR in the rehabilitation of cruciate ligament reconstruction patients improves muscle strength more rapidly than standard ACL protocols. To achieve this a randomised trial with blinding to patients and independent assessor to treatment allocation group will be used with the utilisation of a Humac isokinetic dynamometer.

A randomised controlled pilot study is planned looking at strength improvement of quadriceps and hamstrings of the operated leg between 6, 12 and 24 weeks post-surgery for BFR patients and “sham” BFR. The results will determine if a larger multicentre trial should be considered.

**4 Methods and analysis**

**4.1 Study Design**

This study will be conducted as a randomised controlled trial comparing the application of BFR to standard anterior cruciate ligament repair rehabilitation with sham cuff. The patient and the independent assessor of strength will be blinded to the randomisation allocation.

All patients will receive standard post ACL rehabilitation program provided/overseen by a private physiotherapist. This program will follow the principles set out by “Melbourne ACL rehabilitation Guide 2.0” (Randal Cooper) 43.

In addition to the standard rehab guide all patients will receive bi-weekly “cuff sessions”. As blinding with a cuff is not possible, blinding will be to the patient and measurement team to the pressure applied in the cuff.

**Blinding**

Patients will randomly be assigned to either the 80 percent occlusion (treatment) or 20mmHg (placebo) by usage of an online randomisation tool (Randomiser.org).

The treating physiotherapist will be aware which arm the patient is in, due to the nature of the BFR training, however the patient will not. Assessment of strength, circumference, patient reported outcomes, and knee scores will be conducted by a blinded assessor who is independent of the treating physiotherapist.

**4.1.2 Blood Flow Restriction Intervention**

Pressure will be set to 80 percent limb occlusion pressure (LOP) at rest.

Patients randomized to the BFR cohort receive personalized limb occlusion pressure (LOP) measured using a Doppler ultrasound placed on the dorsalis pedis pulse by the physiotherapist administering the BFR. The LOP will be checked every 2 weeks. Patients in the BFR group are provided a single-chamber manual pneumatic tourniquet (BFR.co) when performing pre-habilitation exercises. set the limb occlusion pressure to 80%, unless the participant reports undesirable pain scores (>5 on a 10 point visual analog scale) associated with the starting cuff pressure around the thigh, then the pressure should be reduced in 10% increments until VAS pain scores are a 5 or less. LOC below 50% would trigger an exclusion of the patient from the BFR study as ‘cuff intolerance’.

BFR training will occur twice weekly beginning 2 weeks following surgery and concluding at 12 weeks post operatively. The BFR training will be carried out in accordance with a 2020 study 44. In utilizing BFR therapy, a standard postoperative rehabilitation protocol will be implemented following the guidelines outlined in the Melbourne ACL Rehabilitation Guide.

The pneumatic cuff will be placed on the proximal thigh to mitigate neurovascular injury. In addition, for the traditional strengthening BFR exercises, four sets should be performed with reps of 30/15/15/15 including 30 second rest interval between each set with the BFR cuff still inflated.

After the completion of each set of exercise, the cuff is deflated for one minute to allow for reperfusion before continuing with the strengthening exercise. The load resistance would be determined preoperatively at 30 percent of maximum resistance during 1 repetition (1RM).

At 12 week post operative mark, patients will be progressed to usual heavy-resistance training and BFR discontinued.

Instead of using percentage repetition maximum, the loads will be adjusted within the first session to meet either the desired repetition scheme or time under tension.

**Control Group**

In the control group, the same cuffs are employed and the same exercise’s are performed with an absolute pressure of to 20 mmHg to allow all the exercises to be performed with the cuff on with no significant occlusion.

Patients will follow the same BFR rehab protocol as above.

The intervention and control groups train separately performed either with a trained physiotherapist or exercise physiologist.

Inventory for physiotherapist for both groups can be found in Appendix 1.

**4.1.4 Physiotherapy Guidelines**

**Prehabilitation**

Before surgery, all patients indeterminant of treatment group will complete a home exercise program by a physiotherapist. The home exercise program consisted of exercises performed 5 times a week for the 2 weeks before surgery as a form of ‘‘prehabilitation.’’ Exercises included quadriceps contractions in end-range extension, straight-leg raises, long-arc quadriceps sets, and quarter squats. All exercises were performed for 75 repetitions with a repetition scheme of 30-15-15-15, allowing for 30 seconds of rest between sets. Patients were educated on how to properly perform the required exercises and were asked to sign a log that would be returned during the preoperative visit to demonstrate compliance.

The physiotherapy program guidelines in appendix 2

**Phase One – 0-6 weeks**

Phase one, also known as the protected phase, begins in the first week post-operatively after day three. The goals of this phase are pain control, reducing effusion within the joint, restoring range of motion, and maintaining muscular and aerobic endurance.

BFR is utilized for a max of 25 minutes during the first phase. For phase one, the exercises are separated into three subsets: weeks one to two, weeks two to four, and weeks four to six.

For weeks one to two, neuromuscular electrical stimulation at 10-20% maximal voluntary contraction is performed for ten minutes with the pad placement distal to the pneumatic cuff on the vastus lateralis and the vastus medialis oblique. The exercise is run with a ten second contraction followed by 20 second rest. Furthermore, the leg is started in full extension before progressing to isometric holds with the leg in 60 to 90 degrees flexion. The second BFR exercise performed is hip adduction while the patient lies on their side. When starting, no weights are present but as the patient progresses through the week, cuff weights should be added. The third exercise performed is bent knee ankle plantar flexion with a light elastic band that is increased for more resistance as the patient progresses. The final BFR exercise of the first two weeks is straight leg raises which once again, begin with no weights with patient progression dictating when cuff weights are added.

For weeks two-four, two new additional exercises are added in addition to the continuation of the exercises from weeks one through two. The exercises from the previous weeks are kept the same with no deviation from how they were performed. One additional exercise added is prone hip extension. This exercise is usually performed with no weights but as the patient progresses, cuff weights are added. Another additional exercise is lifting and straightening one leg to 30-90 degrees know as a long arc quad. This exercise should be performed with no anterior knee pain and no weights until week four.

During weeks four-six, straight leg raises, side-lying hip abduction, and long arc quad continue to be performed by the patient with the same protocol. Again, new BFR exercises are implemented. Bilateral bridging is performed with avoidance of joint line pain. Leg presses are also performed at 0 to 60 degrees with weight at 25% body weight. After the sixth week, progression is made to the second phase of BFR therapy.

**Phase Two – 6-12 weeks**

Phase two places an emphasis on improving strength to progress to a normal, weight-bearing gait as well as achieving full range of motion. Many of the exercises are performed with weights approximately 30% of the one repetition maximum. These exercises mitigate atrophy while beginning the hypertrophic phase. Like phase one, phase two is separated into two subsets: weeks 6-10 and weeks 10-12.

For weeks 6-10, three BFR exercises are performed to strengthen the surrounding muscles. Leg presses at 25% of body weight or 30% of one repetition maximum are performed. Furthermore, resisted hamstring curls are also performed with weights approximately 30% of the one repetition maximum. The final BFR exercise for weeks 6-10, an exercise bike is utilized to build up endurance. The target for the exercise bike is 15 minutes at a resistance level three.

The final section of phase two, weeks 10-12, continues with the exercise bike in building the patient’s endurance. However, squatting is implemented into the exercise regimen. Regular squatting as well as split squatting are performed at weights 30% of the estimated one repetition maximum. At this point, the patient has regained enough muscle to move onto phase three.

**Phase three – After 12 weeks**

Phase three rehabilitation begins three months and beyond status post ACL reconstruction. This involves rotating from high interval intensity training (HIIT) to BFR training until the patient can do HIIT without pain or symptoms. At this point, one weans the patient off of BFR until HIIT is done exclusively.

**4.1.5 Measurement of Muscle strength**

For the study, maximal voluntary contraction (MVC) strength of the knee extensors and flexors will be measured before and after training by a Humac isokinetic dynamometer. For determining maximal voluntary contraction, Humac isokinetic dynamometer has previously been demonstrated to be a reliable and valid tool (Habets et al 2018)

Participants will be seated on the dynamometer chair with back support and secured with straps at the chest, waist, and exercising thigh as shown in Figure ‎1. Maximal knee extension, without hyperextending the knee, will be set as 0° and anatomical zero. The dynamometer chair and arm positions will be altered so that the axis of rotation is aligned with the participant's injured knee joint and recorded for future testing. The resistance pad will be positioned with its farthest end on the anterior lower injured leg, about 2cm proximal to the lateral malleolus.



Figure 1: Participant position during measurement of muscle strength by Isokinetic dynamometer. Image from www.isokinetcs.net

Figure 2 displays a detailed protocol for muscle strength testing. To ensure participant comfort with the dynamometer, a warm-up will be conducted involving reciprocal knee flexion and extension at an angular velocity of 180o/s for one set of ten repetitions. During the warm-up, participants will be instructed not to perform contractions with maximum effort. Following the warm-up, participants will rest for two minutes before proceeding to the isokinetic testing. This involves one set of three repetitions of knee flexion and extension at maximum effort, without any rest in between, with a movement speed of 60°/sec. Participants are prompted to *‘push and pull as fast and as hard as you can*’.

The maximal voluntary isometric concentric torque of the injured knee extensors and flexors will be measured at the knee joint angle of 60o (0o = a knee full extended angle). During the knee isometric strength testing, each participant will perform two trial repetitions with a 30-second rest in between. The participants will be instructed to not apply maximum force during the trial repetitions, as they are intended to warm up their muscles and experience the movement.

For the actual test, the participants will be asked to push or pull as hard as they can against resistance for three seconds. This will be repeated three times, with a 60-second rest between each attempt. The peak torque achieved in each direction during the three maximal contractions for each movement type will be recorded as the participant's maximal strength.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Warm Up (one set of ten repetitions, left knee reciprocal flexion and extension at an angular velocity of 180o/s) | | | | | |
| 60-sec Rest | | | | | |
| Isokinetic knee extension & flexion 60 o /sec (3 reps with no rest) | | | | | |
| 60-sec Rest | | | | | |
| Trial isometric knee extension (2 reps) | | | | | |
| Isometric knee extension | | | | | |
| 1 rep | 30-sec Rest | **1 rep** | 30-sec Rest | **1 rep** | 30-sec Rest |
| Trial isometric knee flexion (2 reps) | | | | | |
| Isometric knee flexion | | | | | |
| 1 rep | 30-sec Rest | **1 rep** | 30-sec Rest | **1 rep** | 30-sec Rest |

Figure 2: Left Knee muscles strength testing step by step protocol

Need to add detail regarding any other outcome measures. Should we include perception measures eg pain, joint confidence? Measures of swelling or other recovery indices

References

Habets B, Staal JB, Tijssen M, van Cingel R. Intrarater reliability of the Humac NORM isokinetic dynamometer for strength measurements of the knee and shoulder muscles. *BMC Research Notes*. 2018;11:15. doi:10.1186/s13104-018-3128-9.

**4.2 Study Locations**

Private Surgical practice of Mr Mulford, Moore, Marshall, Penn, Van Winden and Taylor.

Private Physiotherapy practices in Northern Tasmania

Exercise Physiology and Movement Laboratories, Inveresk Campus, University of Tasmania

**4.3 Study Group**

Surgeons - Mr Mulford, Moore, Marshall, Penn, Van Winden, Taylor and Willemot

Physiotherapists

* ASPR (Lead - Young),
* Physio Tas (Lead - Harberle/Giovanovits),
* Inbalance (Lead - Beeston)

Exercise physiologists –

* UTAS - Williams, Pitchford

Clifford Craig Foundation

* Statistical analysis (Robertson)

**5 Patient Criteria**

Patients presenting to the private rooms of Mr Mulford, Mr Penn, Mr Taylor, Mr Marshall Mr Van Winden and Mr Moore with ACL injury deemed suitable for ACL reconstruction. There is no limit on time between injury and surgery.

They will be offered to participate in the project. Patients will receive informed consent and be reassured that non-participation will in no way affect their medical care.

**5.1 Inclusion criteria**

Between 16 and 50 years old.

ACL injury without concomitant injury requiring post-operative limited weight bearing status or hinge knee brace.

Graft choice Hamstring autograft.

Willingness to participate and provide consent.

**5.2 Exclusion criteria**

Previous significant trauma or surgery to the affected leg including revision ACL surgery.

Significant comorbidity (haemophilia, diabetes, cardiac condition, respiratory condition, etc.)

Concomitant surgery requiring limited weight bearing status post operatively e.g. meniscal repair/ chondral injury requiring NWB status, multi-ligament reconstruction

Patients receiving quadriceps or patella tendon grafts.

Previous deep vein thrombosis

History of bleeding disorders

**6 Allocation**

Will be done by the study coordinator. Patients will randomly be assigned to either the 80 percent occlusion or 20mmHg by usage of an online randomisation tool (ctrandomization.cancer.gov/home/). The group the patient is placed in will be provided to the patients’ physiotherapist. The physiotherapist must not let the patient know if they are in the high or ‘sham’ cuff group.

**7 Outcomes**

**7.1 Primary Outcomes**

Maximal voluntary contraction (MVC) strength of the knee extensors and flexors will be measured by a Humac isokinetic dynamometer. Protocol is in section 4.1.5.

This will be measured preoperatively and postoperatively at 6 weeks, 12 weeks and 24 weeks post surgery.

The change in strength between each time point will be determined for each patient.

**7.2 Secondary Outcomes**

1. Muscle Morphology: Circumference of mid-thigh affect leg and contralateral leg. Circumference measured at the midpoint of the thigh (half way between ASIS and Patella).
2. Physical Function

* Self-reported function was assessed using the International Knee Documentation Committee (IKDC) subjective knee form assesses symptoms and function in activities of daily living. It is scored on a 0–100 scale with 100 representing higher knee function.
* Lysholm Score

VAS pain score at rest and in activity.

**8. Data Collection**

**8.1 Patient Characteristics and Peri-operative Data collected by surgeon**

Pre operative data

* *Age*
* *Sports*
* *Mechanism*
* *Body mass index*
* *Gender*
* *Date of injury*
* *Date of surgery*
* *Time between injury and surgery*

*Surgical data*

* *Graft type*
* *Supplemental surgery (Meniscus, chondral, LET)*

**8.2 Physio recorded Data**

At each BFR session the following is recorded

* Occlusion pressure
* Cuff Pressure used for each session
* Cuff tolerance each session
* Compliance to overall rehabilitation protocol

**8.3 Independent assessment data**

**Exercise physiologist**

**Pre operative and postoperative at 6, 12, 24 weeks**

* *Quadriceps circumference measured 15 cm proximal to the superior pole of the patella*
* *Range of motion*
* Maximal voluntary contraction (MVC) strength of the knee extensors and flexors

**Project manager**

**Will distribute the Physical Function forms for secondary outcomes preoperatively and postoperatively at 6, 12, 24 weeks.**

* *VAS in rest*
* *VAS in activity*
* *Lysholm score*
* *IKDC*

**9. Trial Flow**

**10. Risks**

BFR is associated with a number of complications and risks, including deep venous thrombosis. No instances have been reported in healthy orthopaedic patient populations. However, all participating physiotherapists will be made aware of this potential complication and direct communication with the study coordinator should a suspicion of DVT arise. Treatment and management will be incorporated in the normal postoperative ACL plan. More frequent risks and complications include superficial bruising and pain related to the cuff usage. Patients will be instructed to communicate if such phenomena constitute a reason to interrupt or stop the BFR training. This will also be communicated to the study coordinator.

Patients can remove themselves from this study at ***any*** time without penalty or consequence to their treatment or rehabilitation needs. This will be documented in patient information sheet.

9 Statistical Methods

The study design is a two-group randomised controlled trial of participants post-ACL reconstruction undergoing rehabilitation exercises with high (80%) and low (20mmHg) venous occlusion during the exercises. Measurements of quadriceps strength and mid-thigh circumference will be made at times before and after surgery (**6, 12, 24 weeks)**. The comparative changes in these measures in the two groups will be estimated using repeated-measures multivariate mixed effects linear regression, adjusted for appropriate confounding variables selected by stepwise regression. All the parameters selected for measurement in the trial are considered potential confounding variables, and although the randomised treatment allocation process is intended to create an even distribution of those confounding variables, the relatively small numbers of intended participants leave open the possibility of an uneven distribution of one or more confounders.) The actual timing of follow-up measurements will be treated as random variables in the models.The changes in secondary outcomes measures will be estimated in a similar manner, if there is no significant violation of the assumptions of linear regression, or using repeated-measures multivariate mixed effects ordered logistic regression (a rank-ordered equivalent) if the assumptions are violated. Missing data will be substituted using multiple imputation.

Planned sample size:

1. Due to insufficient evidence in the literature regarding the potential beneficial effects of BFR on knee outcomes, a small sample of 30 patients will be recruited and randomised (15 per group), and an interim analysis performed to supply the numbers for a sample size calculation. This will be a pilot-within-a-trial process.
2. This interim sample size calculation would then tell us the number required to achieve whatever precision and power is required.

10 Funding

Clifford Craig Grant $ 51000 inclusive of GST

[1] Zbrojkiewicz D, Vertullo C, Grayson JE. Increasing rates of anterior cruciate ligament reconstruction in young Australians, 2000-2015. *Med J Aust*. 2018; 208:354-8.

[2] Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg*. 2000; 8:141-50.

[3] Mall NA, Chalmers PN, Moric M, et al. Incidence and trends of anterior cruciate ligament reconstruction in the United States. *Am J Sports Med*. 2014; 42:2363-70.

[4] Brinlee AW, Dickenson SB, Hunter-Giordano A, Snyder-Mackler L. ACL Reconstruction Rehabilitation: Clinical Data, Biologic Healing, and Criterion-Based Milestones to Inform a Return-to-Sport Guideline. *Sports Health*. 2022; 14:770-9.

[5] Palmieri-Smith RM, Lepley LK. Quadriceps Strength Asymmetry After Anterior Cruciate Ligament Reconstruction Alters Knee Joint Biomechanics and Functional Performance at Time of Return to Activity. *Am J Sports Med*. 2015; 43:1662-9.

[6] Williams GN, Snyder-Mackler L, Barrance PJ, Buchanan TS. Quadriceps femoris muscle morphology and function after ACL injury: a differential response in copers versus non-copers. *J Biomech*. 2005; 38:685-93.

[7] Schmitt LC, Paterno MV, Hewett TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2012; 42:750-9.

[8] Hart JM, Pietrosimone B, Hertel J, Ingersoll CD. Quadriceps activation following knee injuries: a systematic review. *J Athl Train*. 2010; 45:87-97.

[9] Hughes L, Paton B, Rosenblatt B, Gissane C, Patterson SD. Blood flow restriction training in clinical musculoskeletal rehabilitation: a systematic review and meta-analysis. *Br J Sports Med*. 2017; 51:1003-11.

[10] Thomas AC, Villwock M, Wojtys EM, Palmieri-Smith RM. Lower extremity muscle strength after anterior cruciate ligament injury and reconstruction. *J Athl Train*. 2013; 48:610-20.

[11] Thomas AC, Wojtys EM, Brandon C, Palmieri-Smith RM. Muscle atrophy contributes to quadriceps weakness after anterior cruciate ligament reconstruction. *J Sci Med Sport*. 2016; 19:7-11.

[12] Urbach D, Nebelung W, Weiler HT, Awiszus F. Bilateral deficit of voluntary quadriceps muscle activation after unilateral ACL tear. *Med Sci Sports Exerc*. 1999; 31:1691-6.

[13] Ithurburn MP, Paterno MV, Ford KR, Hewett TE, Schmitt LC. Young Athletes With Quadriceps Femoris Strength Asymmetry at Return to Sport After Anterior Cruciate Ligament Reconstruction Demonstrate Asymmetric Single-Leg Drop-Landing Mechanics. *Am J Sports Med*. 2015; 43:2727-37.

[14] American College of Sports M. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Med Sci Sports Exerc*. 2009; 41:687-708.

[15] Wengle L, Migliorini F, Leroux T, Chahal J, Theodoropoulos J, Betsch M. The Effects of Blood Flow Restriction in Patients Undergoing Knee Surgery: A Systematic Review and Meta-analysis. *Am J Sports Med*. 2022; 50:2824-33.

[16] Wortman RJ, Brown SM, Savage-Elliott I, Finley ZJ, Mulcahey MK. Blood Flow Restriction Training for Athletes: A Systematic Review. *Am J Sports Med*. 2021; 49:1938-44.

[17] May AK, Russell AP, Della Gatta PA, Warmington SA. Muscle Adaptations to Heavy-Load and Blood Flow Restriction Resistance Training Methods. *Front Physiol*. 2022; 13:837697.

[18] de Queiros VS, Rolnick N, de Alcantara Varela PW, Cabral B, Silva Dantas PM. Physiological adaptations and myocellular stress in short-term, high-frequency blood flow restriction training: A scoping review. *PLoS One*. 2022; 17:e0279811.

[19] Layne AS, Larkin-Kaiser K, MacNeil RG, et al. Effects of blood-flow restriction on biomarkers of myogenesis in response to resistance exercise. *Appl Physiol Nutr Metab*. 2017; 42:89-92.

[20] Laurentino GC, Ugrinowitsch C, Roschel H, et al. Strength training with blood flow restriction diminishes myostatin gene expression. *Med Sci Sports Exerc*. 2012; 44:406-12.

[21] Loenneke JP, Abe T. Does blood flow restricted exercise result in prolonged torque decrements and muscle damage? *Eur J Appl Physiol*. 2012; 112:3445-6; author reply 7-9.

[22] Garcia-Rodriguez P, Pecci J, Vazquez-Gonzalez S, Pareja-Galeano H. Acute and Chronic Effects of Blood Flow Restriction Training in Physically Active Patients With Anterior Cruciate Ligament Reconstruction: A Systematic Review. *Sports Health*. 2024; 16:820-8.

[23] Wernbom M, Augustsson J, Raastad T. Ischemic strength training: a low-load alternative to heavy resistance exercise? *Scand J Med Sci Sports*. 2008; 18:401-16.

[24] Telfer S, Calhoun J, Bigham JJ, et al. Biomechanical Effects of Blood Flow Restriction Training after ACL Reconstruction. *Med Sci Sports Exerc*. 2021; 53:115-23.

[25] Charles D, White R, Reyes C, Palmer D. A Systematic Review of the Effects of Blood Flow Restriction Training on Quadriceps Muscle Atrophy and Circumference Post Acl Reconstruction. *Int J Sports Phys Ther*. 2020; 15:882-91.

[26] Baron JE, Parker EA, Duchman KR, Westermann RW. Perioperative and Postoperative Factors Influence Quadriceps Atrophy and Strength After ACL Reconstruction: A Systematic Review. *Orthop J Sports Med*. 2020; 8:2325967120930296.

[27] Barber-Westin S, Noyes FR. Blood Flow-Restricted Training for Lower Extremity Muscle Weakness due to Knee Pathology: A Systematic Review. *Sports Health*. 2019; 11:69-83.

[28] Trofa DP, Obana KK, Herndon CL, et al. The Evidence for Common Nonsurgical Modalities in Sports Medicine, Part 2: Cupping and Blood Flow Restriction. *J Am Acad Orthop Surg Glob Res Rev*. 2020; 4:e1900105.

[29] Centner C, Wiegel P, Gollhofer A, Konig D. Effects of Blood Flow Restriction Training on Muscular Strength and Hypertrophy in Older Individuals: A Systematic Review and Meta-Analysis. *Sports Med*. 2019; 49:95-108.

[30] Baker BS, Stannard MS, Duren DL, Cook JL, Stannard JP. Does Blood Flow Restriction Therapy in Patients Older Than Age 50 Result in Muscle Hypertrophy, Increased Strength, or Greater Physical Function? A Systematic Review. *Clin Orthop Relat Res*. 2020; 478:593-606.

[31] Okoroha KR, Tramer JS, Khalil LS, et al. Effects of a Perioperative Blood Flow Restriction Therapy Program on Early Quadriceps Strength and Patient-Reported Outcomes After Anterior Cruciate Ligament Reconstruction. *Orthop J Sports Med*. 2023; 11:23259671231209694.

[32] Lu Y, Patel BH, Kym C, et al. Perioperative Blood Flow Restriction Rehabilitation in Patients Undergoing ACL Reconstruction: A Systematic Review. *Orthop J Sports Med*. 2020; 8:2325967120906822.

[33] Devana SK, Solorzano CA, Vail J, Jackson N, Pham D, Jones KJ. Outcomes of Blood Flow Restriction Training After ACL Reconstruction in NCAA Division I Athletes. *Orthop J Sports Med*. 2024; 12:23259671241248589.

[34] Tramer JS, Khalil LS, Jildeh TR, et al. Blood Flow Restriction Therapy for 2 Weeks Prior to Anterior Cruciate Ligament Reconstruction Did Not Impact Quadriceps Strength Compared to Standard Therapy. *Arthroscopy*. 2023; 39:373-81.

[35] Grapar Zargi T, Drobnic M, Jkoder J, Strazar K, Kacin A. The effects of preconditioning with ischemic exercise on quadriceps femoris muscle atrophy following anterior cruciate ligament reconstruction: a quasi-randomized controlled trial. *Eur J Phys Rehabil Med*. 2016; 52:310-20.

[36] Ohta H, Kurosawa H, Ikeda H, Iwase Y, Satou N, Nakamura S. Low-load resistance muscular training with moderate restriction of blood flow after anterior cruciate ligament reconstruction. *Acta Orthop Scand*. 2003; 74:62-8.

[37] Hughes L, Rosenblatt B, Haddad F, et al. Comparing the Effectiveness of Blood Flow Restriction and Traditional Heavy Load Resistance Training in the Post-Surgery Rehabilitation of Anterior Cruciate Ligament Reconstruction Patients: A UK National Health Service Randomised Controlled Trial. *Sports Med*. 2019; 49:1787-805.

[38] Bemben MG, Mitcheltree KM, Larson RD, et al. Can Blood Flow Restricted Exercise Improve Ham:Quad Ratios Better Than Traditional Training? *Int J Exerc Sci*. 2019; 12:1080-93.

[39] Koc BB, Truyens A, Heymans M, Jansen EJP, Schotanus MGM. Effect of Low-Load Blood Flow Restriction Training After Anterior Cruciate Ligament Reconstruction: A Systematic Review. *Int J Sports Phys Ther*. 2022; 17:334-46.

[40] Zargi T, Drobnic M, Strazar K, Kacin A. Short-Term Preconditioning With Blood Flow Restricted Exercise Preserves Quadriceps Muscle Endurance in Patients After Anterior Cruciate Ligament Reconstruction. *Front Physiol*. 2018; 9:1150.

[41] Takarada Y, Takazawa H, Ishii N. Applications of vascular occlusion diminish disuse atrophy of knee extensor muscles. *Med Sci Sports Exerc*. 2000; 32:2035-9.

[42] Kilgas MA, Lytle LLM, Drum SN, Elmer SJ. Exercise with Blood Flow Restriction to Improve Quadriceps Function Long After ACL Reconstruction. *Int J Sports Med*. 2019; 40:650-6.

[43] chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/<https://www.melbourneaclguide.com/docs/ACL_Guide.pdf>.

[44] Humes C, Aguero S, Chahla J, Foad A. Blood flow restriction and its function in post-operative anterior cruciate ligament reconstruction therapy: expert opinion. *Archives of Bone and Joint Surgery*. 2020; 8:570.

Appendex 1 : Inventory required for physiotherapist

|  |
| --- |
| Manual blood flow restriction cuff - BFRco |
| Doppler ultrasound - Edan SD3 Pocket Vascular Doppler |
| Squat rack |
| Leg press |
| Power bands and glute bands |
| Box of various heights |
| 15 and 30 cm hurdles |
| Quad extension machine |
| Hamstring curl machine |
| 15 cm pilates ball |
| Dumbbells |
| Barbell |
| Landmine set up |
| Electrical stimulation |

Appendix 2

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Inner range quad extension** | **Compound movement preparation** | | | **Accessory engagement** | | | | | **Gait Mechanics** | |
|  | **Terminal knee extension\*** | **Squat pattern\*** | **Hinge pattern** | **Single leg triple extension\*** | **Hip flexors** | **Quadriceps\*** | **Hamstring** | **Adductor** | **Calf\*** | **Forwards movement prep\*** | **Lateral movement prep\*** |
| Level 1 | Inner range quads activation over towel | Sit to stand | Romanian deadlift with dowel | Leg press - Double leg | Supine 90/90 | Straight leg raise | Double leg bridge - Isometric | Adductor ball squeeze in sitting | Double leg calf raises | Ladder stepping with crutches | Lateral stepping |
| Level 2 | Terminal knee extension double leg | Goblet squat to box | Romanian deadlift with dumbbells | Leg press - Single leg isometric | Standing 90/90 | Straight leg raise - Ankle weight | Double leg bridge - Isotonic | Side lying leg lift | Double leg calf raises - Weight shift to affected limb | Low hurdle walking with crutches | Crab walk - banded |
| Level 3 | Terminal knee extension single leg | Goblet squat | Romanian deadlift with barbell | Leg press - Single leg isotonic | Standing 90/90 - band resisted | Single leg quad extension - 90 deg isometric | Single leg bridge - Isometric | Copenhagen - Short lever | Single leg calf raises | Low hurdle walking without crutches | Lateral push to base |
| Level 4 | Terminal knee extension single leg - Heel elevated in A frame | Barbell back squat to box | Split stance Romanian deadlift with barbell | Static lunge |  | Single leg quad extension - 90 deg to -30 deg | Single leg bridge - Isotonic |  | Single leg calf raises - Dumbbell loaded | High hurdle walking |  |
| Level 5 | Terminal knee extension single leg - Reverse lunge to A frame | Barbell back squat | Single leg landmine Romanian deadlift | Bulgarian split squat |  |  | Seated hamstring curl - Double leg |  |  | Wall march |  |
| Level 6 | Terminal knee extension single leg - 10 cm box lower to A frame |  |  | Pistol squat to box |  |  | Seated hamstring curl - Single leg |  |  | Wall switch - Single |  |
| Level 7 | Terminal knee extension single leg - 20 cm box lower to A frame |  |  |  |  |  |  |  |  | Wall switch - Triple |  |
| Level 8 | Box step up to A frame |  |  |  |  |  |  |  |  |  |  |
| Level 9 |  |  |  |  |  |  |  |  |  |  |  |