Comparison of quadriceps and hamstring muscle strength after exercises with and without blood flow restriction in the postoperative period of the anterior cruciate ligament: a randomized controlled trial.

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Abstract

BACKGROUND

The anterior cruciate ligament (ACL) reconstruction surgery takes the patient through a period where muscle mass loss occurs. The blood flow restriction combined with strengthening exercises can be an alternative to improve the muscle strength of the quadriceps and hamstrings in the postoperative period of ACL reconstruction.

Objective

Compare the gain in muscle strength between exercises with and without occlusion in the quadriceps and hamstring muscles in the postoperative period of reconstruction of the anterior cruciate ligament.

Methods

This is a randomized, prospective, longitudinal clinical trial, parallel, analytical, experimental type, with random allocation.The study included the participation of postoperative patients, with reconstruction of the anterior cruciate ligament. The isometric muscle strength of knee extension and flexion was evaluated using a digital hand dynamometer and the physical function of the knee, using the Lysholm, KOOS and IKDC questionnaires in the pre -operative and after 4, 8 and 12 weeks. All patients signed a written informed consent form prior to the start of the study

Results

After comparing the rehabilitation of the groups, a statistical difference was observed in quadriceps muscle strength ($p < 0.01$) after 12 weeks and hamstrings ($p < 0.01$) after 8 and 12 weeks in the injured legs. In the analysis of the participants' physical function, there was a significant difference in the Lysholm questionnaire ($p < 0.01$) after 8 and 12 weeks, in the KOOS pain questionnaire ($p < 0.01$) after 4 weeks, symptoms and daily activities ($p < 0, 01$) after 8 and 12 weeks, quality of life ($p < 0.01$) after 12 weeks, and in the IKDC questionnaire ($p < 0.01$) after 8 and 12 weeks.

Conclusion

The blood flow restriction has proved to be efficient for improving muscle strength of the quadriceps, hamstrings and physical function of the knee after reconstruction of the anterior cruciate ligament in early rehabilitation.

Highlights

- Blood flow restriction reduces pain early compared to training without occlusion.
- Subsequent improvement in patients' physical function are observed.
- Benefits are achieved without any detrimental effect on strength.
- Greater strength gains when compared to conventional rehabilitation.
- Blood flow restriction in the early postoperative has been shown to be beneficial.

Background

Delayed rehabilitation after leg trauma and surgeries, such as ACL reconstruction, leads to deficits in muscle strength and endurance, due to muscle atrophy and arthrogenic inhibition, contributing to altering the movement patterns of the involved limb and therefore increasing the risk of early onset of knee osteoarthritis. [1,2]

Atrophy due to disuse of the thigh muscles has been considered important since rehabilitation usually takes a prolonged period of time to reach the original muscle strength, compromising the function of the lower limbs and the patient's quality of life. [3]

There are few studies and protocols whose objective is based on the adequacy of quadriceps and hamstring muscle strength after anterior cruciate ligament reconstruction, which introduce exercises with blood flow restriction (BFR) with 30% of maximum strength.[3,4] It is already known, however, that this occlusion can minimize the risk of injury and contribute to postoperative strengthening. Then, this treatment option requires further investigation in order to refine the protocols related to cuff pressure, exercise dosage and duration, and consequently, enable a better execution of the technique. [5,6,7,8,9]

Therefore, the aim of the present study is to evaluate the intensity of muscle strength gain between exercises with and without occlusion in the quadriceps and hamstring muscles in the postoperative period of the anterior cruciate ligament.

Methods

Study Type

The CONSORT (Consolidated Standards of Reporting Trials) guideline and flowchart for randomized clinical trials was followed in conducting this study.[10] This is a clinical trial, randomized, prospective longitudinal, parallel, analytical, experimental, with random allocation, in which 50% of the participants were in the intervention group and the remaining 50% in the control group. The study included the participation of post-operated patients, with reconstruction of the anterior cruciate ligament. The study was submitted for evaluation by the Ethics Committee of the Federal University of São Paulo and started after approval (Project CEP/UNIFESP n: 0507/2019; CAAE: 12902219.4.0000.5505). Designed by the World Health Organization, its Universal Evaluation Number (UTN): U1111-1242-8567 in 31/10/2019 and also submitted to the Brazilian Registry of Clinical Trials with approval opinion: RBR-9bdgxh in 28/01/2020. All patients signed a written informed consent form prior to the start of the study. The recruitment of participants was conducted after approval by the ethics committee in January 2020 until May 2020.

Participants

A pilot study was conducted, on a small scale, with the same objectives, procedures, materials and methods proposed in the research. Thus, a total of 24 patients were needed, 12 per group. Therefore, to represent a dropout rate of up to 10%, a total of 28 patients were recruited, 14 in each group.

Men and women with anterior cruciate ligament rupture confirmed by medical examination in the last 2 months and planned reconstructive surgery, aged between 18 and 59 years, were included in the study. Exclusion criteria were: new injury or reconstruction of the anterior cruciate ligament due to laxity in the involved limb, patients who needed additional surgical procedures after reconstruction of the anterior cruciate ligament, or infections in the operated region. Previous surgeries on the affected knee, injury to another knee ligament or meniscus were not included. Participants were recruited from the Cohen Institute of Orthopedics, Rehabilitation and Sports Medicine and underwent training at the same location.

Randomization and Allocation

For allocation into groups, randomization was performed in blocks. Each participant had a number that was generated by computer through the website <https://www.random.org/sequences/>, where the smallest value was 1 and the largest, 28. The hidden allocation format was automatically generated through the website, divided into two columns: the first, control group and the second, intervention.

Interventions

The experimental protocol is represented in the figure below, followed by the description of each step of the experiment.

The intervention group used pressure gauges measuring 10 cm x 80 cm in width and a 7 cm x 52 cm pneumatic bag (Cuff Scientific Leg® – WCS, Curitiba, Paraná, Brazil) in the region close to the inguinal ligament of the right and left leg. The control group performed the same proposed exercises without any occlusion material.

To determine the vascular occlusion pressure a portable vascular doppler device (DV-610B®; MEDMEGA, Franca, São Paulo, Brazil) was used. The patient rested for 15 minutes in neutral supine position before the procedure. After resting, with a portable vascular Doppler pen that has an infrared signal transducer, the blood flow over the posterior tibial artery was captured with the aid of a gel. Then the cuff was inflated at the lowest pressure until the arterial pulse was no longer detected, at this time, the pressure value marked on the manometer represented the total occlusion pressure, after this the cuff was deflated.[11,12] During training, 80% of the total occlusion pressure was used. The maximum load tests (1RM) were performed through maximum repetitions in the leg press and flexor chair exercises for training with BFR. 30% of a repetition maximum (RM) was used in each selected exercise in the intervention group and 70% of 1RM in the control group.

In exercises with BFR, four sets were performed, the first always of 30 repetitions, followed by three more sets of 15 repetitions each. With two seconds for concentric contraction and two seconds for eccentric contraction. The rest time in each series was 30 seconds, marked by a digital clock. The pressure must be maintained during the performance of all sets of exercise, if necessary, the pressure can be adjusted at intervals of sets, after the end of the exercise. Between each exercise block, the BFR is released for five minutes, to normalize the blood flow in that region and therefore ensure reperfusion.[13] The training frequency was twice a week for 12 weeks. When the patient could not perform the full movement of one repetition due to fatigue, the exercise was stopped. The control group performed the same exercises, with 70% of 1RM, with three sets of 10 repetitions, with all other parameters, but without BFR. The adherence of the research subjects was registered by an attendance list in each session.

Outcomes

The primary outcome of this study was the assessment of muscle strength using an isometric dynamometer on the first day of assessment and repeated on the last training day of the 4th, 8th and 12th week. The maximum isometric strength of the knee extensors and flexors in both legs was measured using the MICROFET2® digital handheld dynamometer (Hoggan Health Industries, West Jordan, UTAH, USA). The maximum force was recorded in Newtons (N) and collected three times in each leg. Between each contraction there were 60-second intervals. Participants were instructed to remain seated very erect on a chair with their arms crossed in front of their chests and their legs hanging over the edge, knee and hip flexed at 90 degrees. To measure the quadriceps through isometric knee extension, the dynamometer was positioned in the anterior region of the tibia and secured with an inelastic band, in a location identical to the location used in isokinetic dynamometers (five cm proximal to the lateral malleolus), generating stabilization and resistance against movement during the test. To assess the strength of the hamstrings for isometric knee flexion, the dynamometer was attached to the sural triceps region (five cm proximal to the lateral malleolus), and to a table located in front of the participant by an inelastic strap. A demonstration was performed to familiarize the patient with the device before measurements for isometric knee extension and flexion strength began to be collected. Each participant was instructed to perform maximal isometric contractions for five seconds and the maximal strength was recorded.

The secondary outcomes were to analyze physical function of the knee using the Lysholm, IKDC (International Knee Documentation Committee) and KOOS (Knee injury and Osteoarthritis Outcome Score*)* questionnaires. All questionnaires were completed by the patient in order to reduce application bias on the first day of assessment and repeated on the last training day of the 4th, 8th and 12th week.

Sample Size

Sample size calculation was performed using the G*power® 3.1.9.2 Software (Heinrich-Heine-Universität, Düsseldorf, Germany), considering a statistical power of 95% and α=0.05, based on the pilot study and previous studies with distinct populations[7], therefore stipulating a total of 24 patients, 12 in each group. However, a total of 28 patients were recruited, considering an abstinence rate of at least 10%.

Statistical analysis

Data normality and homogeneity were tested using the Shapiro-Wilk and Levene tests, respectively, verifying that the sample did not follow a Gaussian distribution. Descriptive data analysis was performed and expressed as mean and standard deviation. To verify possible differences in the sampling characteristics between the two groups, ANOVA with Greenhouse-Geisser adjustment was used. To analyze the effect of training with vascular occlusion, the Generalized Linear Model of Generalized Estimating Equations (GEE) statistical test was used in which the independent factor was group allocation (control or intervention) and time (week 0, week 4, week 8 and week 12), dependent factor. Effect size was described using Cohen's d as small if 0.20-0.30, medium if 0.40-0.70 and large if greater than or equal to 0.80.

Results

The flow of participants is represented in the diagram below, followed by the description of each step of the experiment.

Data regarding the sample characterization of both groups can be seen in table 1. There was no significant difference (p > 0.05) between the groups regarding age, weight, height and body mass index.

In the injured limb, there was a statistically significant effect of time and group X time interaction (p<0.01 and p<0.01 and d>1.0, respectively), with difference between groups (p=0.01) in the extension movement (figure 4). In the flexion movement of the injured limb, there was a statistically significant effect of time and group X time interaction (p<0.01 and p<0.01 and d>1.0, respectively), with difference between groups (p<0.01) (Table 2).

Table 2. Comparison of muscle strength between groups

Exercises	Leg	Group control (N)	Intervention Group (N)	ES	P-value
Knee extension Pre-surgical	Injured	17,75±0,90	17,50±0,77	0,08	1,00
	Uninjured	21,92±0,66	22,25±0,52	0,15	1,00
Knee Extension 1st Post-surgical	Injured	12,25±1,01	15,50±0,97	0,89	0,43
	Uninjured	19,50±0,95	20,92±0,48	0,51	0,99
Knee Extension 2nd Post-surgical	Injured	13,00±1,04	16,92±0,86	1,11	0,10
	Uninjured	20,42±0,66	22,17±0,45	0,84	0,56
Knee Extension 3rd Post-surgical	Injured	13,83±0,98	19,42±0,55	1,91	<0,01*
	Uninjured	21,58±0,63	23,50±0,52	0,90	0,41
Pre-surgical knee flexion	Injured	10,50±0,46	9,83±0,29	0,47	0,99
	Uninjured	15,42±0,74	14,50±0,73	0,34	1,00
Knee flexion 1st Post-surgical	Injured	7,42±0,45	9,00±0,46	0,95	0,31
	Uninjured	14,25±0,75	14,08±0,79	0,05	1,00
2nd Post-surgical knee flexion	Injured	7,92±0,38	10,33±0,40	1,68	<0,01*
	Uninjured	15,00±0,71	15,08±0,71	0,32	1,00
3rd Post-surgical knee flexion	Injured	8,83±0,35	12,50±0,22	3,39	<0,01*
	Uninjured	15,83±0,67	15,92±0,69	0,33	1,00

N=Newton; ES= Cohen effect size d; *The mean difference is significant at the 0.01 level.

In all groups, an increase in self-reported scores was observed throughout the rehabilitation period, with a statistical difference between the groups, except for the “quality of life” subscale of the KOOS questionnaire (p<0.01 and p=0.06, respectively). Regarding the Lysholm, IKDC questionnaires and all the KOOS subscales (symptoms, pain, daily activity and quality of life), there was a statistically significant group X time interaction (all p<0.01 and d>1.0), time effect (all p <0.01) (Table 3).

Table 3. Comparison of questionnaires between groups

Questionnaires	Groups	Preoperative week mean difference (95% CI)	ES	Mean difference week 1st Post-surgery (95% CI)	ES	Mean difference 2nd week after surgery (95% CI)	ES	Mean difference week 3rd Post-surgery (95% CI)	ES	P-valor
Lysholm	Control	81,17±6,23(69,84-94,84)	0,21	81,75±3,80(74,64-89,54)	0,87	86,17±1,95(82,43-90,07) *	2,72	90,58±0,84(88,96-92,24)	4,31	<0,01
	Intervention	85,17±3,97(77,74-93,31)		92,00±2,39(87,43-96,80)		100,00±0(100,00-100,00) #		100,00±0(100,00-100,00) #		
KOOS										
Symptoms	Control	81,67±6,26(70,27-94,91)	0,39	80,42±4,53(72,01-89,80)	0,97	85,25±2,28(80,89-89,85)	2,07	91,92±0,88(90,21-93,65)	3,53	<0,01
	Intervention	88,42±1,64(85,25-91,70)		92,42±1,29(89,92-94,99)*		98,58±0,93(96,77-100,43) #		100,00±0(100,00-100,00) #		
Pain	Control	84,75±4,67(76,07-94,42)*	0,01	70,67±3,30(64,49-77,43)*	1,66	76,92±3,94(67,57-85,05)*	2,18	88,00±2,35(83,52-92,72)	1,96	<0,01
	Intervention	84,50±3,33(78,22-91,29)*		90,58±3,20(84,52-97,09)*		99,50±0,48(98,57-100,44)* #		100,00±0(100,00-100,00) *#		
Daily activity	Control	86,92±4,44(75,64-93,10)*	0,03	78,83±3,72(71,37-85,97)	0,76	80,58±3,99(73,12-88,81)	1,53	87,50±2,00(83,67-91,51)	2,38	<0,01
	Intervention	83,42±3,37(77,07-90,29)		86,67±1,93(82,97-90,53)*		97,00±0,98(95,10-98,94) *#		99,92±0,08(99,76-100,07*#		
Quality of life	Control	66,42±4,99(57,32-76,96)*	0,12	62,25±4,54(53,96-71,82)	0,81	65,17±4,08(57,63-73,68)	1,29	69,92±3,04(64,20-76,15)	1,72	<0,01
	Intervention	64,33±4,03(56,89-72,75)*		72,58±1,82(69,10-76,25)*		79,75±1,43(77,00-82,60)*		83,92±0,69(82,57-85,28) *		
IKDC	Control	57,67±3,06(51,97-63,99)*	0,22	51,58±2,02(47,77-55,70)*	1,014	55,00±1,60(51,95-58,23)	2,34	60,92±1,59(57,88-64,12)	3,23	<0,01
	Intervention	59,67±1,65(56,52-62,98)		58,25±1,50(55,38-61,27)		65,08±0,38(64,34-65,83) *#		74,83±0,44(73,98-75,70) *#		

KOOS=Knee Injury and Osteoarthritis Outcome Score; IKDC= International Knee Documentation Committee; ES=Cohen's d effect size; *Significant difference p<0.05; #Significant difference in relation to control.

Discussion

In the postoperative phase of training, there is a progressive load on the operated limb. In this manner, the advantages of BFR over resistance training without occlusion reside in the fact that it can initially allow for greater pain reduction, with subsequent improvement in patients' physical function and quality of life - in a higher degree when compared to resistance training without occlusion. These benefits are achieved without any detrimental effect on strength, including greater strength gains when compared to groups that perform conventional physical therapy rehabilitation, as observed in the present study.

This study was the first to use a portable isometric dynamometer to measure the muscle strength of knee extensors and flexors during the first months of rehabilitation after anterior cruciate ligament reconstruction. We also use, in order to promote the well-being of patients, validated functionality questionnaires previously used in other works on the same topic. The use of the isometric dynamometer ensured in a validated way, observed in previous studies[14,15,16,17], the assessment of muscle strength for knee extension and flexion in early rehabilitation with practical execution and data analysis. In this way, any major strains on the knee that could be caused by an isokinetic dynamometer were avoided, in addition to the low cost and ease of transport when comparing the two devices.

As other authors[18,3,19], this study applied the technique of BFR individually, ensuring safety for all patients and respecting their individualities. Safety in our study was obtained through the use of portable Doppler ultrasound in all patients, offering 80% occlusion during training individually.[11,12]

Our research used a consistent protocol, with low loads, large training volume and 80% precise occlusion pressure in the intervention group during all sessions. In exercises with BFR, four sets were performed, the first always of 30 repetitions, followed by three more sets of 15 repetitions each. Similar applicability used in other studies.[18,3] The protocols used in this study reflect current guidelines for training with BFR[18,3,5,21,1], in addition to proposed objectives for the best possible rehabilitation after ACL reconstruction.

In addition to evaluating the isometric muscle strength of the quadriceps, our work was also the first to test the isometric muscle strength of the hamstrings with a portable dynamometer preoperatively and right after ACL surgical reconstruction: at 4, 8 and 12 weeks. Important clinical improvements were observed both in the intervention group and in the control group, but the group that used BFR and lower training load showed a significant improvement in muscle strength in a shorter rehabilitation period than in the group in which the rehabilitation was performed with a higher charge.

The hamstrings were possibly stronger previously than the quadriceps muscle due to the greater arthrogenic muscle inhibition of the quadriceps, decreasing sensory reception and information sent to the frontal cortex. This manifestation is commonly observed in the first days of the post-surgery period, as the ligament makes this connection between the peripheral nervous system and the central nervous system.

Another associated issue that may have contributed to the early strengthening of the hamstrings is the fact that patients could have used the posterior leg muscles in the exercise leg press using contractions together with the quadriceps, performing movement compensation during execution, even with all the execution guidelines and correct positioning on the device. In addition, we train later on the flexor chair making a muscle isolation contraction, which further increases the strength of this musculature. Future studies could analyze this aspect with electromyography in this initial phase of post-surgical training. There were no significant differences in strength in the uninjured legs.

Regarding knee extension, in our study, we observed that before surgery, patients did not have differences. After comparing the rehabilitation groups, a statistical difference was observed in quadriceps muscle strength ($p<0.01$) after 12 weeks of training in the group with vascular occlusion, findings similar to those found in the study by HUGHES et al.[3], but he achieved a significant difference in quadriceps muscle strength in a leg press unilaterally ($p<0.01$) after 8 weeks. In the fourth and eighth weeks there were progressive improvements, but without significance in our study. Regarding the uninjured leg, there were no differences in any period.

When analyzing the questionnaires[22,23,24] in the pre-surgical period, the patients did not have differences in any group. In the first evaluation, the only statistical difference was in the KOOS questionnaire in the pain subtopic ($p<0.01$) after 4 weeks in the group that trained with BFR and with low load. This data revealed a key factor for the patients to be able to progress consequently in all other items evaluated during the treatment, possibly due to the comfort and security they felt with the low load during the execution of the movements and the muscle strengthening of the region promoted by the occlusion. The KOOS questionnaire in the subtopics symptoms and daily activities presented ($p<0.01$) after 8 and 12 weeks and quality of life ($p<0.01$) after 12 weeks, where the answers involved many behavioral psychological questions and not just motor ones. The IKDC questionnaire showed statistical difference ($p<0.01$) after 8 and 12 weeks. A similar fact occurred with the Lysholm questionnaire, which obtained a significant difference ($p<0.01$) after 8 and 12 weeks, demonstrating the importance of pain improvement for early gain in strength and physical function.

The present study observed that the application of BFR in the early postoperative phase has been shown to be beneficial in terms of muscle strength and physical function of patients. During this period, high-intensity exercise is not possible and the benefits of metabolic stress on protein synthesis can be activated. Thus, training with BFR can be a preparatory approach and prior to high-intensity resistance exercises, especially in the presence of pain or when high loads are not tolerated/allowed.[18,3,25]

We suggest that in clinical practice the use of BFR with low loads should be integrated with exercises with higher loads in more advanced stages of rehabilitation in an intercalated way, as this may stimulate other important musculoskeletal adaptations during treatment after ACL reconstruction.

There were no adverse effects such as deep vein thrombosis, skin lesions, hematomas or any damage during the research in any patient. However, in the first trainings, it was possible to observe that the individuals presented discomfort with the technique due to compression in the inguinal region, fatigue during exercises and hyperemia in the thigh due to the increased blood supply to the region, findings that improved with the removal of the occlusion in a few seconds. This was due to the novelty of training with BFR associated with edema in the knee region, which is considered normal after the recent surgical procedure, promoting such sensations. Similar findings were also described before[24,18,3], suggesting that the light load associated with BFR in the early post-surgical phases may not exacerbate pain or inflammation in the knee joint in the days following training, which may positively influence the volume of exercise during sessions and patient adherence to a rehabilitation program. Thus, it was observed in our sample that early reduced pain plays a fundamental role in the patient's functionality and quality of life.

Therefore, future researches with larger sample sizes, specific groups of grafts, ages and in a multicentric design are suggestions that aim to further increase the reach of the generalization of the approached theme.

Limitations

The current study has some limitations that should be considered, participants could not be blinded due to the intervention model using the cuffs. The study also has a relatively short follow-up time, but performed during the period in which patients could have the best benefits from the application of the technique, which is in this initial post-surgical phase. The sample was relatively small, but sufficient according to the sample size calculation and randomization ensured sample homogeneity.

Conclusion

The findings of the present study show that after comparing training with 30% of one repetition maximum using BFR and with 70% of maximum repetition without occlusion, the group that used BFR was statistically shown to have a faster gain in improvement of quadriceps muscle strength, hamstrings, and physical function of the knee after anterior cruciate ligament reconstruction in an early rehabilitation program.

Abbreviations

Blood flow restriction (BFR)

Anterior cruciate ligament (ACL)

Declarations

Ethics approval and consent to participate

The study was submitted for evaluation by the Ethics Committee of the Federal University of São Paulo and started after approval (Project CEP/UNIFESP n: 0507/2019; CAAE: 12902219.4.0000.5505). Designed by the World Health Organization, its Universal Evaluation Number (UTN): U1111-1242-8567 in 31/10/2019 and also submitted to the Brazilian Registry of Clinical Trials with approval opinion: RBR-9bdgxh in 28/01/2020.

Consent for publication

All patients signed a written informed consent form prior to the start of the study.

Availability of data and material

All data are available for publication.

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Authors' contributions

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Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing-original draft, Writing-review & editing

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Supervision

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Data curation, Formal analysis

Melo MEV

Writing-review & editing

Competing interests

The authors declare no conflicts of interest.

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References

1. Žargi T, Drobnič M, Stražar 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 Aug 24;9:1150. doi: 10.3389/fphys.2018.01150. PMID: 30197599; PMCID: PMC6118218.
2. Sonnery-Cottet B, Saithna A, Quelard B, Daggett M, Borade A, Ouanezar H, Thaunat M, Blakeney WG. Arthrogenic muscle inhibition after ACL reconstruction: a scoping review of the efficacy of interventions. *Br J Sports Med*. 2019 Mar;53(5):289-298. doi: 10.1136/bjsports-2017-098401. Epub 2018 Sep 7. Erratum in: Br J Sports Med. 2019 Dec;53(23):e8. PMID: 30194224; PMCID: PMC6579490.
3. Hughes L, Rosenblatt B, Haddad F, Gissane C, McCarthy D, Clarke T, Ferris G, Dawes J, Paton B, Patterson SD. 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 Nov;49(11):1787-1805. doi: 10.1007/s40279-019-01137-2. PMID: 31301034.

4. Iversen E, Røstad V, Larmo A. Intermittent blood flow restriction does not reduce atrophy following anterior cruciate ligament reconstruction. *J Sport Health Sci*. 2016 Mar;5(1):115-118. doi: 10.1016/j.jshs.2014.12.005. Epub 2015 Apr 18. PMID: 30356481; PMCID: PMC6188575.
5. Lipker LA, Persinger CR, Michalko BS, Durall CJ. Blood Flow Restriction Therapy Versus Standard Care for Reducing Quadriceps Atrophy After Anterior Cruciate Ligament Reconstruction. *J Sport Rehabil*. 2019 Nov 1;28(8):897-901. doi: 10.1123/jsr.2018-0062. PMID: 30300054.
6. Barber-Westin S, Noyes FR. Blood Flow-Restricted Training for Lower Extremity Muscle Weakness due to Knee Pathology: A Systematic Review. *Sports Health*. 2019 Jan/Feb;11(1):69-83. doi: 10.1177/1941738118811337. Epub 2018 Nov 26. PMID: 30475660; PMCID: PMC6299354.
7. Lixandrão ME, Ugrinowitsch C, Berton R, Vechin FC, Conceição MS, Damas F, Libardi CA, Roschel H. Magnitude of Muscle Strength and Mass Adaptations Between High-Load Resistance Training Versus Low-Load Resistance Training Associated with Blood-Flow Restriction: A Systematic Review and Meta-Analysis. *Sports Med*. 2018 Feb;48(2):361-378. doi: 10.1007/s40279-017-0795-y. PMID: 29043659.
8. Nascimento DDC, Petriz B, Oliveira SDC, Vieira DCL, Funghetto SS, Silva AO, Prestes J. Effects of blood flow restriction exercise on hemostasis: a systematic review of randomized and non-randomized trials. *Int J Gen Med*. 2019 Feb 12;12:91-100. doi: 10.2147/IJGM.S194883. PMID: 30863135; PMCID: PMC6388738.
9. Schoenfeld BJ, Grgic J, Krieger J. How many times per week should a muscle be trained to maximize muscle hypertrophy? A systematic review and meta-analysis of studies examining the effects of resistance training frequency. *J Sports Sci*. 2019 Jun;37(11):1286-1295. doi: 10.1080/02640414.2018.1555906. Epub 2018 Dec 17. PMID: 30558493.
10. Schulz KF, Altman DG, Moher D; CONSORT Group. CONSORT 2010 statement: updated guidelines for reporting parallel group randomised trials. *BMJ*. 2010 Mar 23;340:c332. doi: 10.1136/bmj.c332. PMID: 20332509; PMCID: PMC2844940.
11. Laurentino GC, Ugrinowitsch C, Roschel H, Aoki MS, Soares AG, Neves M Jr, Aihara AY, Fernandes Ada R, Tricoli V. Strength training with blood flow restriction diminishes myostatin gene expression. *Med Sci Sports Exerc*. 2012 Mar;44(3):406-12. doi: 10.1249/MSS.0b013e318233b4bc. PMID: 21900845.
12. Laurentino GC, Loenneke JP, Mouser JG, Buckner SL, Counts BR, Dankel SJ, Jessee MB, Mattocks KT, Iared W, Tavares LD, Teixeira EL, Tricoli V. Validity of the Handheld Doppler to Determine Lower-Limb Blood Flow Restriction Pressure for Exercise Protocols. *J Strength Cond Res.* 2020 Sep;34(9):2693-2696. doi: 10.1519/JSC.0000000000002665. PMID: 29912080.
13. Patterson SD, Hughes L, Warmington S, Burr J, Scott BR, Owens J, Abe T, Nielsen JL, Libardi CA, Laurentino G, Neto GR, Brandner C, Martin-Hernandez J, Loenneke J. Blood Flow Restriction Exercise: Considerations of Methodology, Application, and Safety. Front Physiol. 2019 May 15;10:533. doi: 10.3389/fphys.2019.00533. Erratum in: *Front Physiol*. 2019 Oct 22;10:1332. PMID: 31156448; PMCID: PMC6530612.
14. Lesnak J, Anderson D, Farmer B, Katsavelis D, Grindstaff TL. Validity of hand-held dynamometry in measuring quadriceps streght and rate of torque development. *Int J Sports Phys Ther*. 2019 Apr;14(2):180-187. PMID: 30997270; PMCID: PMC6449009.
15. Almeida GPL, Albano TR, Melo AKP. Hand-held dynamometer identifies asymmetries in torque of the quadriceps muscle after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2019 Aug;27(8):2494-2501. doi: 10.1007/s00167-018-5245-3. Epub 2018 Oct 30. PMID: 30377716.
16. Hansen EM, McCartney CN, Sweeney RS, Palimenio MR, Grindstaff TL. Hand-held Dynamometer Positioning Impacts Discomfort During Quadriceps Strength Testing: A Validity and Reliability Study. *Int J Sports Phys Ther*. 2015 Feb;10(1):62-8. PMID: 25709864; PMCID: PMC4325289.
17. Koblbauer IF, Lambrecht Y, van der Hulst ML, Neeter C, Engelbert RH, Poolman RW, Scholtes VA. Reliability of maximal isometric knee strength testing with modified hand-held dynamometry in patients awaiting total knee arthroplasty: useful in research and individual patient settings? A reliability study. *BMC Musculoskelet Disord*. 2011 Oct 31;12:249. doi: 10.1186/1471-2474-12-249. PMID: 22040119; PMCID: PMC3229470.
18. Hughes L, Paton B, Haddad F, Rosenblatt B, Gissane C, Patterson SD. Comparison of the acute perceptual and blood pressure response to heavy load and light load blood flow restriction resistance exercise in anterior cruciate ligament reconstruction patients and non-injured populations. *Phys Ther Sport*. 2018 Sep;33:54-61. doi: 10.1016/j.ptsp.2018.07.002. Epub 2018 Jul 10. PMID: 30014968.
19. Curran MT, Bedi A, Mendias CL, Wojtys EM, Kujawa MV, Palmieri-Smith RM. Blood Flow Restriction Training Applied With High-Intensity Exercise Does Not Improve Quadriceps Muscle Function After Anterior Cruciate Ligament Reconstruction: A Randomized Controlled Trial. Am *J Sports Med*. 2020 Mar;48(4):825-837. doi: 10.1177/0363546520904008. PMID: 32167837.
20. Giles L, Webster KE, McClelland J, Cook JL. Quadriceps strengthening with and without blood flow restriction in the treatment of patellofemoral pain: a double-blind randomised trial. *Br J Sports Med*. 2017 Dec;51(23):1688-1694. doi: 10.1136/bjsports-2016-096329. Epub 2017 May 12. PMID: 28500081.
21. Tennent DJ, Hylden CM, Johnson AE, Burns TC, Wilken JM, Owens JG. Blood Flow Restriction Training After Knee Arthroscopy: A Randomized Controlled Pilot Study. *Clin J Sport Med*. 2017 May;27(3):245-252. doi: 10.1097/JSM.0000000000000377. PMID: 27749358.
22. Metsavaht L, Leporace G, Riberto M, de Mello Sposito MM, Batista LA. Translation and cross-cultural adaptation of the Brazilian version of the International Knee Documentation Committee Subjective Knee Form: validity and reproducibility. *Am J Sports Med*. 2010 Sep;38(9):1894-9. doi: 10.1177/0363546510365314. Epub 2010 May 14. PMID: 20472755.
23. Peccin MS, Ciconelli R, Cohen, M. Questionário específico para sintomas do joelho "*Lysholm Knee Scoring Scale*": tradução e validação para a língua portuguesa. *Acta ortop. bras*. 2006, 14(5):268-72.
24. Gonçalves RS, Cabri J, Pinheiro JP, Ferreira PL. Cross-cultural adaptation and validation of the Portuguese version of the Knee injury and Osteoarthritis Outcome Score (KOOS). *Osteoarthritis Cartilage*. 2009 Sep;17(9):1156-62. doi: 10.1016/j.joca.2009.01.009. Epub 2009 Mar 11. PMID: 19303082.
25. 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 Feb;74(1):62-8. doi: 10.1080/00016470310013680. PMID: 12635796.
26. 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 Sep;40(10):650-656. doi: 10.1055/a-0961-1434. Epub 2019 Jul 23. PMID: 31342480.

Tables

Due to technical limitations, Table 1 is only available as a download in the Supplemental Files section.

Figures

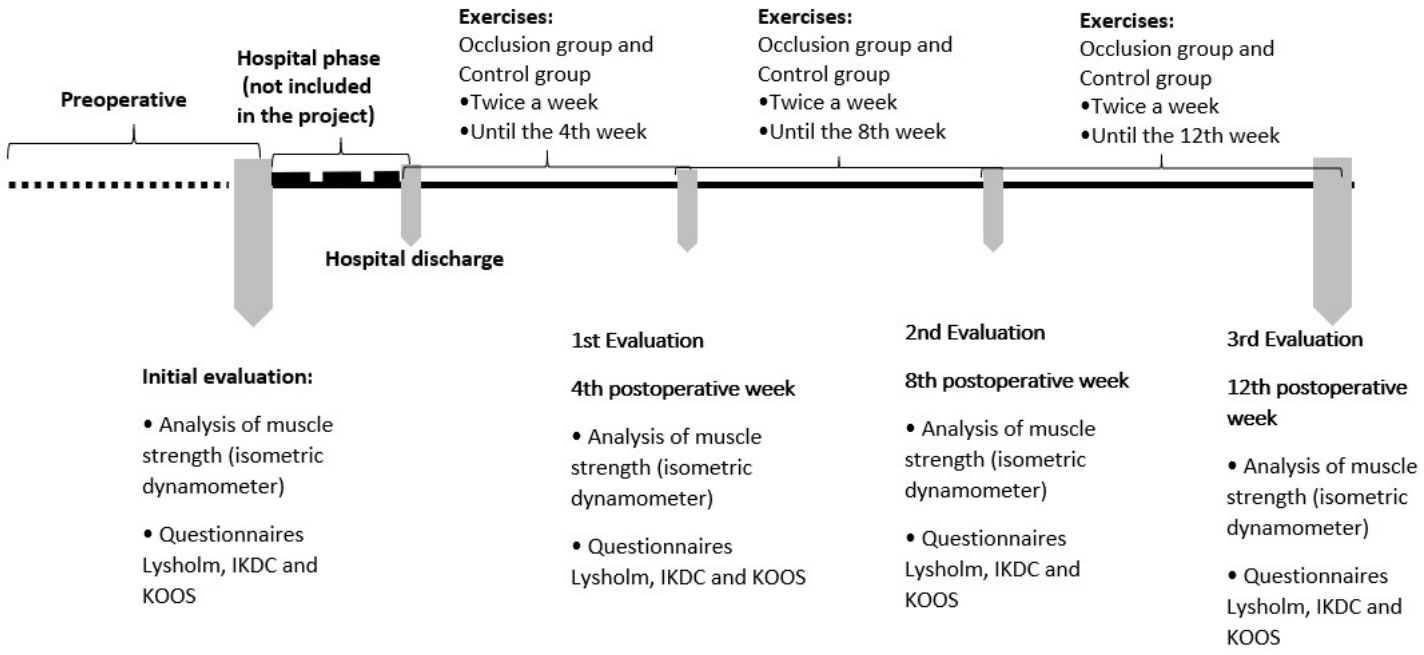

Figure 1

Overview of the experimental study protocol

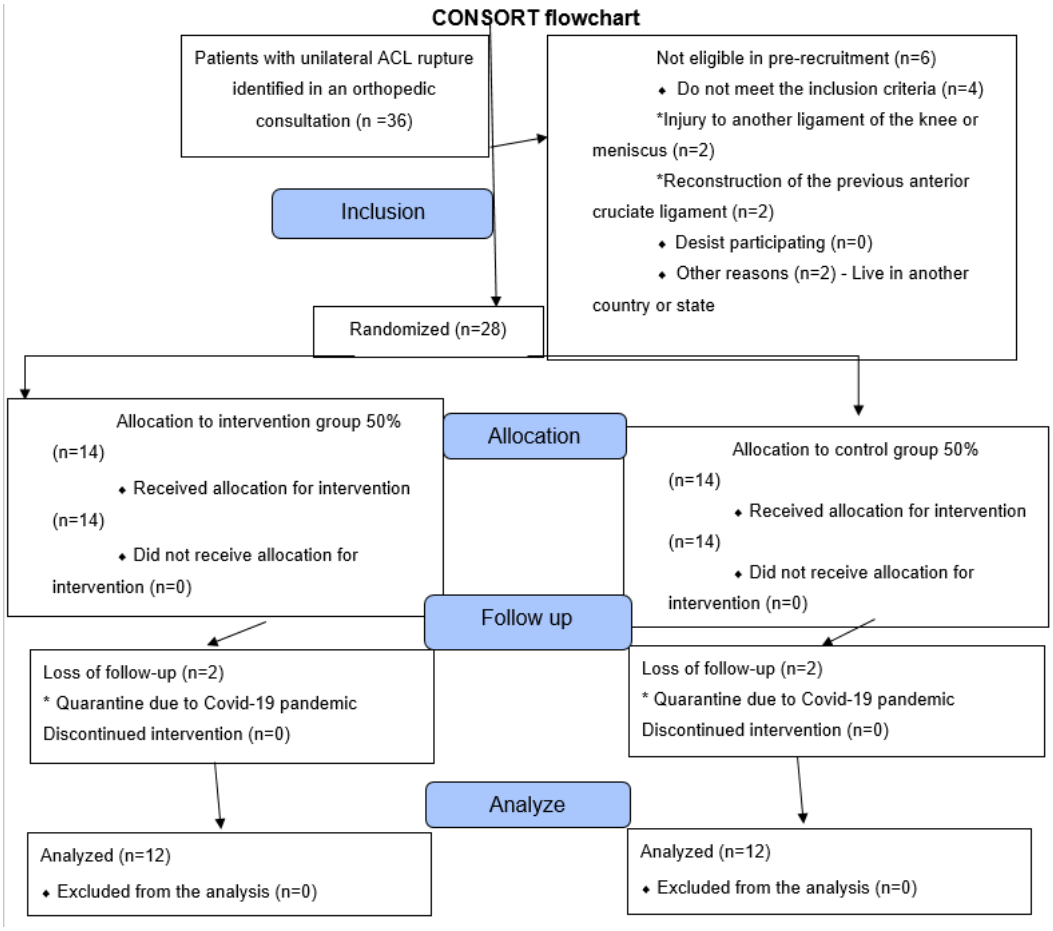

Figure 2

Study flowchart overview

Supplementary Files

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- Table1.docx