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Effects of Rehabilitation Exercise with Blood Flow Restriction after Anterior Cruciate Ligament Reconstruction

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Abstract: The present study examined the effects of a rehabilitation exercise program with blood flow restriction (BFR) vs. a general rehabilitation exercise program in patients who have undergone anterior cruciate ligament (ACL) reconstruction. Among a total of 24 patients, the general rehabilitation exercise group (GRE, $n = 12$) and blood flow restriction group (BFR, $n = 12$) were assigned the same. The GRE group conducted a general rehabilitation exercise, and the BFR group conducted a BFR exercise along with the general rehabilitation exercise. All participants performed the rehabilitation exercise program session for 60 min three times a week for 12 weeks under supervision. All dependent parameters (Lysholm score and International Knee Documentation Committee (IKDC) subjective score, muscle activity, isokinetic muscular function, Y-balance test) were evaluated before and after the rehabilitation exercise program. GRE improved the Lysholm score, IKDC subjective score and Y balance test (posterior-medial, posterior-lateral) ($p < 0.05$). Moreover, BFR was effective in improving the Lysholm score and IKDC subjective score and muscle activity (e.g., vastus medialis oblique during isokinetic contraction and rectus femoris during isometric contraction), isokinetic function (e.g., peak torque and total work) and Y-balance test (e.g., anterior, posterior medial, posterior lateral) ($p < 0.05$). Our study confirmed that a rehabilitation exercise program with BFR after ACL reconstruction is a more effective rehabilitation modality for improving muscle activity during muscle contraction and muscle function compared with GRE. Therefore, it is recommended to use BFR as an effective rehabilitation program for rapid recovery after ACL reconstruction.

Keywords: anterior cruciate ligament reconstruction; blood flow restriction; rehabilitation exercise; muscle activity; muscle function

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1. Introduction

Leisure activities are increasing among modern people, and they are trying to experience various cultures. Among them, participation in sports is increasing not only for physical health but also for adventure sports that exceed one's limits [1,2]. In terms of public health, an increase in the population participating in sports is a very important and necessary activity for health, but sports injuries may also occur due to excessive competition, incorrect skills, and immaturity of skill. As such, sports injuries, which were previously limited to athletes, occur frequently in the public due to the increase in sports participation [3].

Sports injuries are typically brought on by musculoskeletal conditions that affect the bones, muscles, ligaments, tendons and nerves [4]. These conditions have a variety of side effects, including decreased muscle strength and endurance, muscle atrophy, joint degeneration, a reduction in cardiopulmonary endurance, harmed proprioception and confidence loss. As a result, it is becoming more crucial to prevent, treat and recover from sports injuries [5,6].

The knee joint is the most active joint in sports, and injuries frequently occur during exercise [7]. In particular, the anterior cruciate ligament (ACL) is the most important structure of the knee joint and is responsible for maintaining the stability of the knee joint [8]. Injuries to the ACL are most commonly caused by internal rotational forces acting on the tibia relative to the femur, but they are frequently caused by extrinsic mechanisms and intrinsic mechanisms [9,10].

After surgical treatment for an ACL injury, the joint range of motion (ROM) and extension and flexion movements are limited while the injured area is fixed for a long period of time, resulting in weakening of the quadriceps and hamstrings. In this way, after ACL reconstruction, it is important to restore the function of the previous level of competitiveness through a rehabilitation exercise program so that the patient can safely return to daily life and sports as soon as possible [11–13].

The rehabilitation exercise program for an ACL injury progresses step by step, including ROM exercise, weight-bearing, isokinetic muscle exercise, proprioception exercise and functional exercise, in parallel with physical therapy [10,12,14]. However, weakened quadriceps and muscle function may increase the risk of re-injury and arthritis when using high-intensity loads or performing strenuous exercises for rapid recovery. Therefore, there is a need for effective treatments, even at low intensities.

Recently, blood flow restriction (BFR) training developed by Dr. Yoshiaki Sato has been recommended, and BFR limits blood flow to muscles with the Kaatsu Master device, inducing a hypoxic environment in muscles and resulting in effective muscle hypertrophy and muscle strength improvement [15,16]. Previous research found that combining BFR and resistance exercise could improve muscle function and hypertrophy while having the same effect as high-intensity resistance exercise treatment despite low intensity [17].

Most of the exercise programs related to BFR are being conducted for athletes, the elderly or the general public, and there is a lack of studies that have combined BFR treatment with the rehabilitation exercise program after an ACL reconstruction. Therefore, the purpose of this study was to examine the effect on the improvement in quadriceps muscle function, muscle hypertrophy and functional ability of the knee through complex exercise using BFR added to the existing rehabilitation process after ACL reconstruction of the knee.

2. Materials and Methods

2.1. Participants

Thirty patients with an ACL injury who were having acute reconstruction or planning were included in our research. Four of them were eliminated because they had suture surgery for an associated cartilage injury, their original muscle strength did not decline as a result of chronic damage, or they were elite athletes. A total of 26 patients were assigned to the general rehabilitation exercise group (GRE, n = 13) and the blood flow restriction group (BFR, n = 13) according to age, gender, height and weight. All participants underwent ACL reconstruction by an authorized knee orthopedic surgeon at M Hospital using the autograft transplantation method, and rehabilitation training was performed by a rehabilitation team trainer with a physical therapy certificate and rehabilitation degree at the same hospital. All evaluations were performed the same way before ACL reconstruction and after the 12-week rehabilitation exercise program. All participants were required to visit the hospital rehabilitation center for 12 weeks, three times a week. For a period of 12 weeks, all participants were forced to visit the hospital rehabilitation facility three times each week. One participant from each group who had poor participation rates were eliminated, and we analyzed the final 24 participants (age: 29.3 ± 8.0 years, male: n = 18, female: n = 6) for the study. The physical characteristics of the participants and the CONSORT (Consolidated Standards of Reporting Trials) flowchart are shown in Table 1 and Figure 1, respectively.

Table 1. Participants' characteristics.

Variable	GRE (n = 12)	BFR (n = 12)	p-Value
Sex (men/women)	9/3	9/3	-
Age (yr)	27.83 ± 8.43	30.83 ± 7.59	0.370
Height (cm)	170.27 ± 8.80	172.58 ± 4.76	0.431
Weight (kg)	78.68 ± 18.63	71.98 ± 10.05	0.288
ACL leg (right/left)	6/6	3/9	-

Values are expressed as the mean ± standard deviation. GRE, general rehabilitation exercise group; BFR, blood flow restriction group; ACL, anterior cruciate ligament.

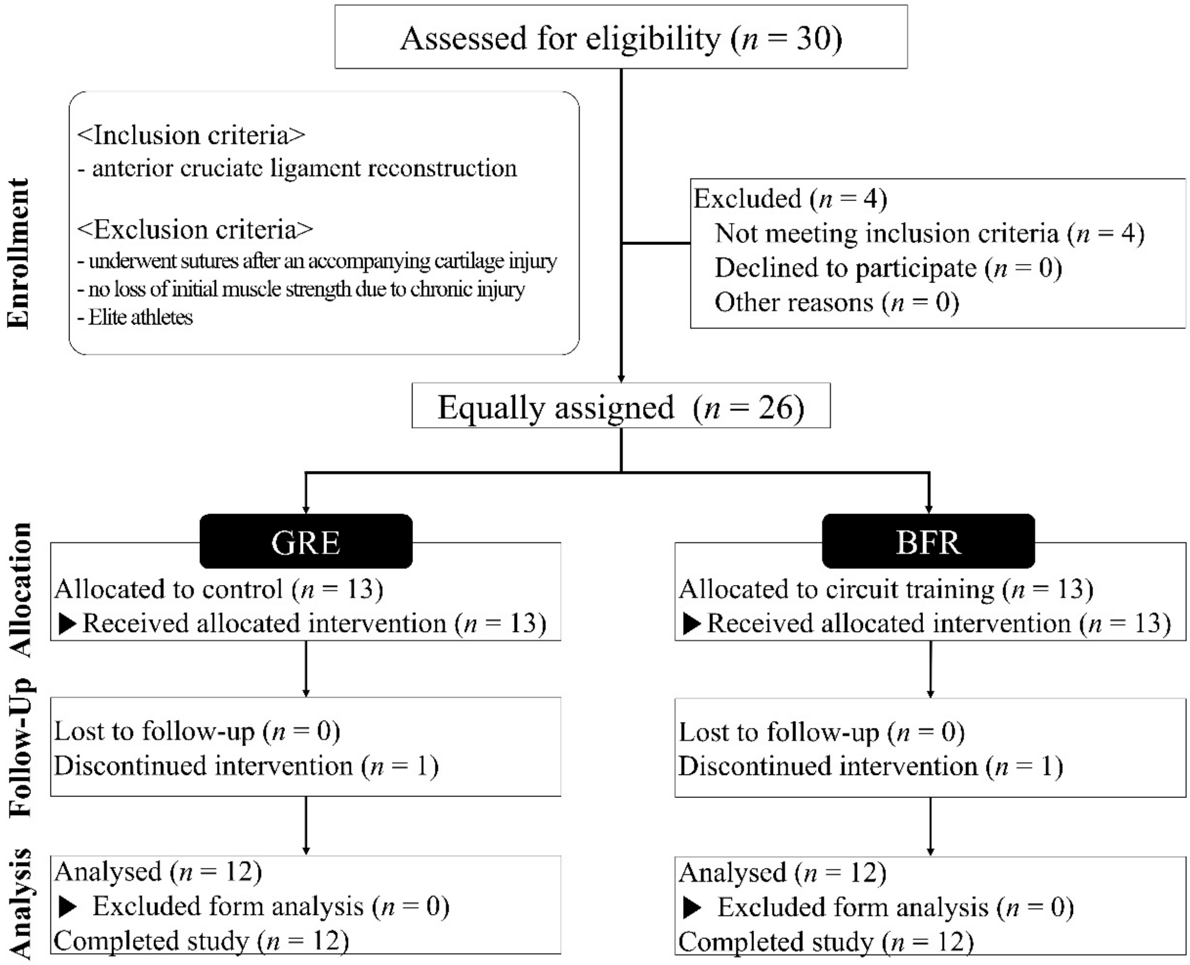

Figure 1. CONSORT flowchart. GRE, general rehabilitation exercise group; BFR, blood flow restriction group.

All participants received information about the purpose and process of the study, including possible side effects, and consent was obtained. As shown in Table 1, there were no significant differences in the participants' characteristics between the groups. All procedures were in accordance with the ethical standards of the responsible committee on human experimentation. The study was approved by the Institutional Review Board of Konkuk University (7001355-202210-E-180) in Korea and was conducted according to the Declaration of Helsinki.

2.2. Study Design

The present study design is illustrated in Figure 2. All participants underwent a pre-test, a 12-week rehabilitation exercise program and a post-test. After the participant's ACL rupture had been identified by an orthopedic surgeon, pre-tests were conducted. The pre-test was completed 1 day before the ACL reconstruction, and the post-test was conducted 2 days after the last rehabilitation exercise program. On the test day, all participants visited the Sports Medical Center at M Hospital and were tested after stabilization. All participants visited the rehabilitation center at M Hospital three times a week for 12 weeks and performed GRE and BFR exercises with a trainer supervision for a total of 60 min. The GRE group conducted a general rehabilitation exercise, and the BFR group conducted a BFR exercise along with the general rehabilitation exercise. Before and after the 12-week rehabilitation exercise session, all participants underwent anthropometry (i.e., height and weight) and the Lysholm score and the IKDC subjective score was determined, as well as muscle activity (e.g., quadriceps femoris), isokinetic muscular function (e.g., strength and endurance) and balance (e.g., Y-balance anterior, Y-balance posterior medial and Y-balance posterior lateral). All measurements were conducted at the rehabilitation center of M Hospital, and the room temperature and humidity were maintained at 23 ± 2 °C and 50 ± 5%. All patients came to the hospital between 9:00 and 10:00 a.m. to have their measurements taken. As for the measurement clothes, short-sleeved shirts and shorts provided by the rehabilitation center at M Hospital were worn.

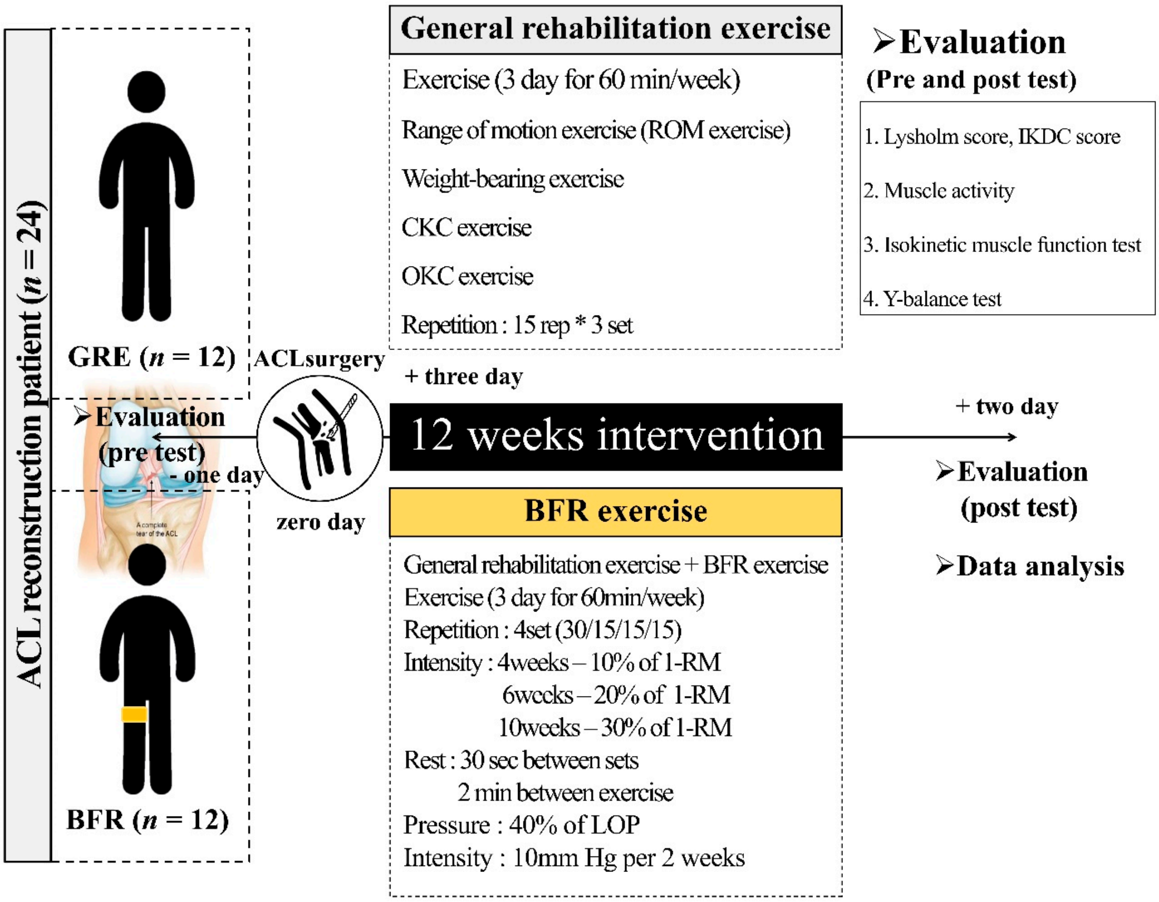

Figure 2. Study design. GRE, general rehabilitation exercise group; BFR, blood flow restriction group; CKC, closed kinetic chain; OKC, open kinetic chain; IKDC, International Knee Documentation Committee; ROM, range of motion; ACL, anterior cruciate ligament.

2.3. Anthropometry (Height and Weight)

Height and weight were measured using a height and weight measuring instrument (BSM330, Inbody, Seoul, Republic of Korea). All participants wore lightweight clothing and were asked to remove all metal items on their body.

2.4. Lysholm Score and the International Knee Documentation Committee (IKDC) Subjective Score

All participants measured the Lysholm score and the IKDC subjective score, which evaluate the patient's subjective knee functional status as clinical evaluation items.

The Lysholm score is a relatively simple measurement method for evaluating the health status of the knee joint by measuring symptoms in daily life caused by ACL and meniscus injuries. This questionnaire consists of eight items, with a total score of 100 points, with a higher score indicating fewer symptoms and a higher level of functioning. The IKDC score was designed to measure patients with ligament and meniscus injuries as well as knee disorders such as patellofemoral pain or symptoms, and measure the function in daily life and sports activities. This questionnaire consists of seven knee symptoms items, two sports activities items and two functions items, with a higher score indicating fewer symptoms and a higher level of functioning.

2.5. Muscle Activity

The muscle activity of the quadriceps femoris was evaluated while performing isometric contraction and isokinetic contraction at 60°/s. Participants underwent a surface electromyography (EMG) test that applied maximum force to the quadriceps femoris muscle in a sitting position on the floor with the knees extended. An EMG test of the vastus medialis oblique (VMO), rectus femoris (RF) and vastus lateralis oblique (VLO) was conducted. The EMG was performed using a wireless surface electromyography (TeleMyo DTS, Noraxon co., Scottsdale, AZ, USA), and the electrode had a diameter of 22 mm. After converting the surface EMG analog signal coming from each channel into a digital signal, it was stored and analyzed using software (MR-XP, Noraxon co., AZ, USA) on a computer.

2.6. Isokinetic Muscle Function

The isokinetic muscle function (e.g., strength and endurance) was measured using an isokinetic dynamometer (Biodex system IV, Biodex Medical Systems Inc., New York, NY, USA) in the quadriceps femoris and hamstrings. Muscle strength was evaluated using peak torque measured three times at an angular velocity of 60°/s, and muscle endurance was evaluated using 10 measurements at an angular velocity of 180°/s.

2.7. Y-Balance Test

The Y-balance test (YBT) for measuring dynamic balance ability was measured using FMS's YBT Kit (Functional Movement Systems, Inc., Chatham, VA, USA). The subjects arrived in the laboratory, maintained a stable state for about 30 min and then proceeded with the Y-balance test. The point at which the balance is maintained while standing in the center of the Y-balance board and stretching one leg in each direction of anterior, posteromedial and posterolateral was measured in cm. This test was measured twice in each direction while standing barefoot, where the highest measurement value was recorded. If the supporting foot falls off the ground, supports the floor with the extended foot to balance or fails to return to the starting position after stretching the foot, it is considered a failure and measured again [18].

2.8. Rehabilitation Exercise Program

The rehabilitation exercise program was performed 3 days per week for 12 weeks. The general rehabilitation exercise session consisted of exercise to enhance range of motion (ROM exercise), weight-bearing exercise, closed kinetic chain (CKC) exercise and open kinetic chain (OKC) exercise. The ROM exercise was designed to promote recovery of full ROM within 6 weeks. The ROM exercise was performed passively for knee flexion, and then proceeded with active assistance. In addition, from week 4, active motion was performed for complete full ROM. The ROM exercise increased gradually in the controlled pain and swelling. Then, weight-bearing exercises were performed with the knees completely extended, such as a weight shift exercise.

From week 3, all patients were trained to walk normally as much as possible. We recommended the patients to wear braces until week 12. To ensure complete extension of the knee, the angle of the brace was fixed at 0° until week 2; the patients were permitted to adjust the brace to their desired angle after week 2. The CKC exercises were initiated 2–3 weeks after surgery, such as wall squat, mini squat, half squat, and lunge, step-up exercise, and added a gradual increase in weight from week 9. The exercise was performed in three sets of 15 repetitions. The OKC exercises for the quadriceps femoris were performed 2–6 weeks after surgery without weight bearing.

From week 7, OKC exercises training with increased weight was performed at a limited angle of 90–45° flexion and was performed without angle restriction from 3 months after surgery. Additionally, the OKC exercises for the hamstring muscle were initiated 4 weeks after surgery, such as prone active curl and standing active curl exercise, and added a gradual increase in weight from week 9. All GRE were performed in three sets of 15 repetitions. The rehabilitation exercise program conducted in this study is shown in Figure 3.

Exercise	Weeks of program				
	0-2	3-4	5-6	7-8	9-12
1. Range of motion					
0-90°	o				
0-130°		o			
2. Stretching (hamstring femoris and quadriceps muscle)	o	o	o	o	o
3. Muscle strength (Q-set, SLR, active leg extension)	o	o			
4. CKC (gait retraining, squat, heel raise)		o	o	o	o
5. OKC					
Leg extension (90~60°)				o	o
Leg curl (non-weight)		o	o		
Leg curl (weight)				o	o
6. Proprioception training					
Weight shifting, cup walking	o	o			
One leg balance		o	o	o	
7. Perturbation					o

Figure 3. Rehabilitation exercise program. Q-set, quadriceps femoris muscle setting exercise; SLR, straight leg elevation, CKC, closed kinetic chain exercise; OKC, open kinetic chain exercise.

The BFR group performed the same ROM exercises and weight-bearing exercises as the GRE group, and applied 4 weeks after surgery. The BFR group performed the exercise by applying BFR when performing the same CKC exercise and OKC exercise as the GRE group. The BFR group used the Smart Cuffs device (Smart Cuffs PRO, Smart Tools Plus LLC, OH, USA) with the general rehabilitation program. The BFR application method was the method proposed by Patterson et al. [19]. The intensity of exercise was started by setting 10–30% of 1-RM (repetition maximum), and was gradually increased. The BFR was achieved using hand-pumped blood pressure cuffs. The pressure was applied at 40% of the systolic blood pressure (SBP), and was applied by 10 mmHg per 2 weeks.

2.9. Sample Size

In this study, the G*power® Version 3.1.9.2 Software was used to calculate the minimum sample size. The maximum power threshold reported in Tenent et al. [20] was used to calculate the priori sample size required for repeated measurement variance analysis. A total of 24 participants were required to obtain a statistical power of 95% at an effect size of d = 0.6 and $\alpha = 0.05$, including two conditions and two measurement points.

2.10. Statistical Analysis

All statistical analyses were conducted using SPSS version 25.0 (IBM Corp., Armonk, NY, USA) for Windows. Data are presented as mean ± standard deviation. The normality of the distribution of all outcome variables was verified using the Shapiro–Wilk test. A two-way analysis (time × group) of variance with repeated measures of the "time" factor was used to analyze the effects of rehabilitation exercise programs on each dependent variable. Partial eta-squared (η^2) values were calculated as measures of the effect size. If a significant interaction or main effect within time or between group was found, the paired *t*-test or independent *t*-test was used. The level of significance was set a priori at $p < 0.05$.

3. Results

Changes in the Lysholm score and IKDC subjective score via rehabilitation intervention in each group are shown in Table 2. Except for the main impact of time, there was no significant interaction in the Lysholm score ($p < 0.001$ $\eta^2 = 0.623$) and the subjective IKDC score ($p < 0.001$, $\eta^2 = 0.533$). Post-hoc analysis found a significant increase of the Lysholm score in GRE ($p < 0.01$) and BFR ($p < 0.001$) via the rehabilitation exercise program after ACL reconstruction. Additionally, a significant increase was found for the IKDC subjective score in GRE ($p < 0.05$) and BFR ($p < 0.001$).

Table 2. Changes in the Lysholm score and IKDC subjective score via rehabilitation intervention in each group.

Variables	Group	Intervention		Mean Change 95% CI	p (η^2) Value		
		Before	After		Group	Time	Interaction
Lysholm score (points)	GRE	69.17 ± 11.94	83.08 ± 6.32	13.92 [4.92, 22.92] **	0.835 (0.002)	0.000 (0.623) †	0.158 (0.089)
	BFR	63.67 ± 21.82	86.50 ± 12.27	22.83 [12.87, 32.80] ***			
IKDC score (points)	GRE	62.39 ± 14.11	73.25 ± 9.94	10.86 [0.27, 21.45] *	0.971 (0.000)	0.000 (0.533) †	0.290 (0.051)
	BFR	59.55 ± 12.04	76.42 ± 14.32	16.87 [10.83, 22.91] ***			

Values are expressed as the mean ± standard deviation. CI, confidence interval; GRE, general rehabilitation exercise group; BFR, blood flow restriction group; IKDC, International Knee Documentation Committee. Significant interaction or main effect: † $p < 0.05$; Significant difference in each group via rehabilitation intervention: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The muscle activities of VMO, VLO and RF during constant velocity contraction through rehabilitation intervention in each group are shown in Table 3. There was a significant interaction in the muscle activity of VMO ($p = 0.009$, $\eta^2 = 0.269$) during isokinetic contraction. In addition, there was a significant main effect over time in the muscle activity of VMO ($p = 0.003$, $\eta^2 = 0.334$) and RF ($p = 0.019$, $\eta^2 = 0.224$) during isometric contraction. Post-hoc analysis found that a significant increase of VMO ($p < 0.001$) RF ($p < 0.05$) during isometric contraction in BFR.

Table 4 shows the isokinetic muscle function through rehabilitation intervention in each group. The main effects of interaction and time appeared on hamstring peak torque ($p < 0.006$, $\eta^2 < 0.301$) and total work ($p < 0.008$, $\eta^2 = 0.280$). In the quadriceps femoris, the main effects of time appeared on peak torque ($p = 0.005$, $\eta^2 = 0.311$) and total work ($p = 0.015$, $\eta^2 = 0.240$). Post-hoc analysis found that a significant increase of peak torque ($p < 0.01$) and total work ($p < 0.05$) in BFR.

Table 3. Changes in muscle activity of VMO, VLO and RF during isokinetic contraction via rehabilitation intervention in each group.

Variables	Group	Intervention		Mean Change 95% CI	p (η^2) Value		
		Before	After		Group	Time	Interaction
VMO isokinetic contraction (mV)	GRE BFR	177.79 ± 66.42 148.49 ± 42.84	186.00 ± 65.98 255.95 ± 82.82	8.21 [−54.90, 71.33] 107.47 [63.87, 151.06] ***	0.334 (0.042)	0.003 (0.334) †	0.009 (0.269) †
VLO isokinetic contraction (mV)	GRE BFR	223.72 ± 125.83 225.04 ± 73.96	253.26 ± 104.75 255.95 ± 82.82	29.54 [−26.41, 85.48] 30.91 [−12.01, 73.83]	0.957 (0.000)	0.072 (0.139)	0.966 (0.000)
RF isokinetic contraction (mV)	GRE BFR	178.93 ± 74.05 184.14 ± 67.75	204.48 ± 74.85 214.09 ± 61.09	25.55 [−13.24, 64.33] 29.96 [0.91, 59.00] *	0.780 (0.004)	0.019 (0.224) †	0.843 (0.002)

Values are expressed as the mean ± standard deviation. GRE, general rehabilitation exercise group; BFR, blood flow restriction group; VMO, vastus medialis oblique; VLO, vastus lateralis oblique; RF, rectus femoris. Significant interaction or main effect: † $p < 0.05$; Significant difference in each group via rehabilitation intervention: * $p < 0.05$, *** $p < 0.001$.

Table 4. Changes in isokinetic muscle function via rehabilitation intervention in each group.

Variables	Group	Intervention		Mean Change 95% CI	p (η^2) Value		
		Before	After		Group	Time	Interaction
Quadriceps femoris strength (N-M)	GRE BFR	121.70 ± 44.48 94.08 ± 35.89	139.42 ± 48.06 131.08 ± 47.23	17.72 [−13.15, 48.59] 37.00 [14.46, 59.54] **	0.268 (0.056)	0.005 0.311) †	0.279 (0.053)
Hamstring strength (N-M)	GRE BFR	66.43 ± 22.90 53.17 ± 22.25	72.10 ± 18.22 80.50 ± 23.73	5.67 [−6.92, 18.25] 27.33 [18.27, 36.40] ***	0.770 (0.004)	0.000 (0.499) †	0.006 (0.301) †
Quadriceps femoris endurance (J)	GRE BFR	648.86 ± 234.07 632.08 ± 277.06	700.29 ± 224.12 899.83 ± 322.70	51.43 [−121.89, 224.76] 267.75 [65.56, 469.94] *	0.325 (0.044)	0.015 (0.240) †	0.088 (0.127)
Hamstring endurance (J)	GRE BFR	377.34 ± 146.88 414.08 ± 178.12	412.31 ± 117.34 633.33 ± 207.91	34.97 [−53.01, 122.95] 219.25 [112.21, 326.29] **	0.043 (0.173) †	0.001 (0.426) †	0.008 (0.280) †

Values are expressed as the mean ± standard deviation. GRE, general rehabilitation exercise group; BFR, blood flow restriction group; N-M, Newton-Meters; J, Joule. Significant interaction or main effect: † $p < 0.05$; Significant difference via rehabilitation intervention in each group: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 5 showed a significant interaction for Y-balance anterior ($p = 0.046$, $\eta^2 = 0.170$) and posterior lateral ($p < 0.048$, $\eta^2 = 0.167$). There was also a substantial main effect of time for Y-balanced posteromedial ($p < 0.001$, $\eta^2 = 0.583$). Post-hoc analysis found that Y-balance anterior significantly increased via intervention in BFR ($p < 0.01$) and Y-balance posterior medial (GRE, $p < 0.05$; BFR, $p < 0.001$) and Y-balance posterior lateral (GRE, $p < 0.05$; BFR, $p < 0.05$) significantly increased via intervention in all groups.

Table 5. Changes in balance via rehabilitation intervention in each group.

Variables	Group	Intervention		Mean Change 95% CI	p (η^2) Value		
		Before	After		Group	Time	Interaction
Y-balance anterior (cm)	GRE BFR	48.50 ± 8.42 44.17 ± 6.51	51.50 ± 5.98 51.67 ± 7.57	3.00 [0.00, 6.00] 7.50 [3.92, 11.08] **	0.454 (0.026)	0.000 (0.526) †	0.046 (0.170) †
Y-balance posterior medial (cm)	GRE BFR	89.92 ± 9.88 86.08 ± 6.54	95.92 ± 6.19 93.58 ± 5.48	6.00 [1.37, 10.63] * 7.50 [4.81, 10.19] ***	0.263 (0.056)	0.000 (0.583) †	0.544 (0.017)
Y-balance posterior lateral (cm)	GRE BFR	89.00 ± 7.91 83.75 ± 13.25	91.42 ± 7.84 93.17 ± 7.38	2.42 [0.19, 4.64] * 9.42 [2.42, 16.42] *	0.618 (0.011)	0.002 (0.364) †	0.048 (0.167) †

Values are expressed as the mean ± standard deviation. GRE, general rehabilitation exercise group; BFR, blood flow restriction group. Significant interaction or main effect: † $p < 0.05$; Significant difference via rehabilitation intervention in each group: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

4. Discussion

Increasing the general public's risk of knee injury from sports activities lies in incorrect epidemiological movements and disproportionate muscle function. It is considered important to understand the biomechanics of physical movements necessary for sports to prevent injuries first and to try to eliminate the risk of injury through game analysis. However, this study attempted to provide an effective exercise program for an ACL injury that most frequently appears in knee joint injuries [21–23].

After surgical treatment due to an ACL injury, the patient can relieve pain through rehabilitation, recover joint function, improve walking and daily living performance and quickly return to daily life [24]. However, immediately after surgery, the muscle strength and activity of the thigh are reduced to half of those before surgery, muscle atrophy occurs by 5 to 20% and joint function deteriorates, accompanied by severe pain due to the incision. Lack of adequate initial rehabilitation treatment can result in low thigh muscle strength and activity and persistent functional impairment, leading to premature disability, falls and a reduced ability to perform activities of daily living [25]. Therefore, restoring lost muscle strength to normal levels is very important. Traditionally, physiotherapy and exercise have been performed for the rehabilitation of patients after surgery, but it is said that successful effects cannot be achieved due to the adjustment of exercise intensity and the patient's anxiety due to pain. In contrast, it is determined that a new rehabilitation exercise method is necessary.

Blood flow restriction (BFR) was a method of inducing a hypoxic environment in tissues by restricting blood flow to the muscles by applying pressure to the arms and legs using a device during exercise [19]. Even short-term training at a relatively low intensity (20–30% of 1-RM) can provide similar effects to existing high-intensity training and has been used by various groups such as the public, athletes and patients with illnesses. Therefore, this study investigated the effect of muscle function improvement, muscle hypertrophy and knee functional ability of the quadriceps muscles by performing a 12-week complex exercise using BFR added to the existing rehabilitation process of patients with weakened quadriceps muscles due to ACL reconstruction.

Hughes et al. [26] conducted an evaluation of the Lysholm score and IKDC subjective score through 8 weeks of BFR and traditional high-intensity resistance training rehabilitation exercises in patients undergoing ACL reconstruction. The BFR-applied group showed a greater effect than the resistance training rehabilitation group. Vieira de Melo et al. [27] also reported that the Lysholm score and IKDC subjective score showed significant improvement in the BFR group as a result of a study comparing the BFR group and the control group. The results of this study also showed that Lysholm score and IKDC subjective score were improved through rehabilitation exercise, but it was found that the effect of improvement was better in the group that underwent combined BFR treatment.

Consistent with the results of this study, applying systematic rehabilitation exercises to patients with an ACL injury may reduce knee joint build and muscle atrophy, improve muscle function and reduce muscle defect rates. Additionally, an increase in joint ROM appears to contribute to knee joint stabilization. In this way, early rehabilitation exercises can improve the knee joint function score, and it is thought that a greater effect will appear, especially when BFR is added.

Improving muscle function and muscle activity after ACL surgery is important, and Ohta et al. [28] reported that BFR exercise for 16 weeks significantly improved knee extensor and flexor muscle power in ACL patients, and Kacin et al. [29] reported that BFR exercise increased knee extensor strength and endurance. In addition, Vieira de Melo et al. [27] reported that hamstring muscle strength was significantly increased through BFR rehabilitation exercise after ACL surgery for 12 weeks, showing results consistent with this study. Several studies have been reported on the improvement of muscle function in relation to BFR, but there is a lack of research related to muscle activity in ACL patients. Tang et al. [30] found that a low-intensity electrical stimulation program resulted in significant improvements in VMO, VLO and RF, and Ng et al. [31] compared muscle activation through an 8-week biofeedback exercise program, showing relative reports that there was a significant increase in active in VMO and VLO. VMO and RF were significantly improved in this study as well, and it is judged that the BFR exercise program is effective for muscle activity in relation to the improvement of isokinetic muscle function, as in previous studies.

Hughes et al. [26] showed significant improvement in Y-balance performance as a result of combined treatment with BFR and resistance exercise for 8 weeks after ACL surgery, and Ladlow et al. [32] reported that BFR and low-intensity resistance exercise for 3 weeks. As a result of the combined treatment, the Y-balance performance was significantly improved. In addition, Werasirirat and Yimlamai [33] reported that the Y-balance test significantly improved as a result of the combined treatment of physical therapy and BFR exercise for 4 weeks. In particular, more effective results were found in the group treated with BFR, and the results of this study also showed that the Y-balancing performance was better in the group treated with BFR than in the general rehabilitation group, showing consistent results.

In order to bring about improvements in muscle function, metabolic stress induced through proper muscle mechanical tension and exercise, damage to the integrity of individual muscle fibers by destroying the skeletal muscle structure and induction of cellular responses through stimulation of the mTOR pathway are proposed [34]. In this way, given that the improvement of muscle function occurs with appropriate stimulation, we carefully predict that the stimulation of BFR exercise implemented in this study was an appropriate program that could show positive changes in muscle function and muscle activity improvement. A key challenge in rehabilitative exercise programs is to design optimal training programs that promote neural and muscle adaptations while keeping biological healing constraints and safety in mind. In BFR, muscle function improves, muscle hypertrophy occurs, the intramuscular environment changes to hypoxia and acidity, metabolites accumulate locally, growth inhibitory factors decrease to restore this and growth promoting factors increase, promoting muscle satellite cell proliferation [35]. In addition, m-TOR signaling pathway activity enhances protein synthesis initiation [36], increases the activity of many motor units, including fast-twitch fibers [37], and causes metastatic muscle hypertrophy [38]. This theoretical background supports the muscle strength-enhancing effect of BFR exercises.

Manipulation of various BFR-related variables can affect muscle strength and size, including training volume, exercise intensity load, training frequency, exercise variation, contraction type and recovery between efforts [19,39]. Tramer et al. [40] found that BFR therapy for 2 weeks before ACL reconstruction had no effect on quadriceps muscle strength compared to standard therapy. In addition, Curran et al. [41] reported that a high-intensity BFR exercise intervention, repeating 4 sets of 10 repetitions twice a week for 8 weeks, did not significantly improve the muscle function, activation or volume of the quadriceps muscle. However, in the study of Kilgas et al. [42], even a long time after ACL surgery, as a result of performing BFR exercise for 25 min, 5 days a week for 4 weeks, the maximum muscle strength increased by 20 $\pm$ 14%, and the left and right muscle balance improved. As such, BFR exercise should not be performed before ACL reconstruction, and it is important to perform low-intensity exercise after reconstruction, since high-intensity exercise does not have a positive effect. In particular, it is judged that BFR exercise will be effective in improving muscle function not only in early applications after surgery but also in patients who have not received long-term rehabilitation.

Previous studies have suggested that arterial occlusive pressure (AOP) is an important variable for successful rehabilitation [43], and it was reported that a load equivalent to 20–40% of an individual's maximum strength level (e.g., 1-RM) is highly likely to maximize muscle growth and strength [44]. In this study, the BFR strength was used at 10–30% of 1RM, so it was judged to be appropriate in terms of exercise intensity. In addition, Hwang et al. [45] reported that BFR exercise induces greater oxygen utilization and changes in the endocrine system. In particular, since carbohydrate metabolism is increased during exercise, it is reported that BFR exercise will bring about a low-intensity, high-intensity effect. Because high-intensity rehabilitation after ACL reconstruction can cause patients to feel burdened with pain and recurrence of injury, low-intensity exercise programs such as BFR have shown effective results despite low intensities. It is thought that BFR can increase the effectiveness of rehabilitation.

This study had several limitations. First, this was a retrospective study. There are several equally important initial patient characteristics to consider when randomly assigning patients to groups (physical activity level, legs, preoperative muscle deficit, genetic muscle fiber type ratio, pain intensity, anxiety level, etc.). Differences between groups on some traits may have interfered with the results, because it is nearly impossible in a clinical setting to combine groups by all potential confounders. Second, preoperative physical activity and dietary intake were not considered. Evaluation results may vary depending on the patient's physical ability and gender. Third, the 3-month follow-up period was relatively short. Fourth, it focuses only on specific stages of rehabilitation, and the sample size may not be representative of the overall population.

5. Conclusions

Our study confirmed that a rehabilitation exercise program with the BFR after ACL reconstruction is a more effective rehabilitation modality for improving muscle activity during muscle contraction and muscle function compared with GRE. Therefore, it is recommended to use BFR as an effective rehabilitation program for rapid recovery after ACL reconstruction. However, there was no clear difference in the subjective knee function evaluation questionnaire and Y-balance test. Future studies should use ultrasound and magnetic resonance imaging (MRI) to elucidate the mechanisms of muscle activity and hypertrophy in patients who underwent ACL reconstruction. In addition, research is needed to verify the effects of promoting energy metabolism and increasing thigh muscle strength when BFR is applied to improve health.

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