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Original Article

Adding Blood Flow Restriction to Strengthening Exercises in Management of Patellofemoral Pain Syndrome

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Abstract

Objectives: This study compared the efficacy of conventional strengthening exercises versus strengthening combined with blood flow restriction training (BFRT) in patients with patellofemoral pain syndrome (PFPS). **Methods**: In this double-blinded randomized controlled trial, fifty patients were randomly allocated to either a strengthening exercise group or a strengthening with BFRT group for six weeks (three sessions/weekly). Primary outcome was quadriceps strength. Secondary outcomes included pain (Visual Analogue Scale), hip abductor strength (Hand-Held Dynamometer), function (Kujala questionnaire), joint position sense (JPS), and dynamic postural control (Star Excursion Balance Test [SEBT]). Assessments occurred at baseline, three, and six weeks. **Results**: Both groups showed significant improvements in all measures. However, the BFRT group demonstrated significantly greater improvements in quadriceps strength, pain, and hip abductor strength at three and six weeks. Functional scores were significantly better in the BFRT group only at six weeks. No significant inter-group differences were found for JPS or SEBT at any time point. **Conclusions**: This study provides preliminary evidence supporting the addition of BFRT to strengthening exercises for PFPS to enhance quadriceps strength, reduce pain, and improve hip strength and function. However, given the short follow-up, small sample size, and lack of additional benefits for proprioception and balance, these findings should be considered preliminary. **ClinicalTrials.gov ID**: NCT06565754

Keywords: Blood Flow Restriction, Patellofemoral Pain Syndrome, Strengthening Exercises, Visual Analogue Scale

Introduction

A common musculoskeletal condition, patello-femoral pain syndrome (PFPS) is characterized by generalized anterior knee pain that is usually made worse by running, squatting, kneeling, negotiating stairs, and prolonged sitting. The condition frequently stems from patellar mal-tracking and aberrant patello-femoral joint loading occurring within the context of lower-extremity muscular weakness and overuse patterns. PFPS is highly prevalent among young and physically active individuals, with considerable impact on participation in sport and daily activities, and symptoms may persist or recur over the long term if not adequately managed[1-3].

Impairments associated with PFPS extend beyond pain to include quadriceps weakness, hip abductor weakness, altered lower-limb kinematics, proprioceptive deficits, and functional limitations[1,4,5].

Quadriceps weakness represents one of the predominant clinical characteristics and demonstrates associations to progression of patellofemoral joint degeneration, emphasizing the importance of restoring muscle strength as a key rehabilitation target[4]. Therefore, lower-extremity muscle strength remains critical for appropriate patellofemoral joint loading and stability during gait and functional tasks; thus, enhancing quadriceps strength may improve physical function and decrease joint stress in

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individuals with PFPS[5].

Proprioception, specifically joint position sense (JPS), contributes significantly to articular stability, neuromuscular coordination, and postural equilibrium. Deficits in knee JPS have been correlated with compromised movement control patterns and elevated injury susceptibility[6,7].

The relationship between patellofemoral joint pain and proprioceptive deficits appears to originate from malalignment-induced changes in joint loading and afferent input[8]. Mal-tracking and abnormal patellofemoral contact pressures may disturb mechanoreceptor function and peripatellar neural input, leading to altered proprioceptive feedback and instability of the patella[8]. In PFPS, this may manifest as reduced accuracy of knee JPS and impaired neuromuscular control during functional activities[6,7,9].

Conservative management of PFPS traditionally emphasizes quadriceps and hip musculature strength, often combined with flexibility, neuromuscular, and functional training[2,10]. Rehabilitation protocols targeting hip abductors have demonstrated meaningful improvements in pain, strength, and function among individuals with knee pathologies, supporting the integration of proximal strengthening in PFPS rehabilitation[11,12].

However, high-load resistance exercises, which are often required to optimize muscle hypertrophy and strength, may not be well tolerated in patients with PFPS due to pain provocation during weight-bearing and open-chain loading[10,13]. Blood flow restriction training (BFRT) has evolved as an alternative therapeutic modality permitting low-load resistance exercise to elicit strength and hypertrophic changes comparable to high-load training through partial arterial inflow restriction and venous outflow occlusion using pneumatic cuffs[13-15]. BFRT generates a hypoxic and metabolically demanding intramuscular environment that enhances lactate accumulation, muscle-derived myokines, and anabolic signaling cascades, thereby stimulating muscular hypertrophy and strength gains despite employing reduced external loads[16-19].

However proposed mechanisms include exercise-induced hypoalgesia, conditioned pain modulation, and increased endogenous opioid and endocannabinoid activity contributing to post-exercise analgesia[20-24].

Evidence addressing BFRT specifically within PFPS populations remains scarce. A randomized trial in individuals with patellofemoral pain reported that low-load quadriceps strengthening combined with BFRT produced greater reductions in pain during daily activities and similar or superior strength gains compared with standard high-load strengthening[10]. More recently, BFRT combined with hip- and knee-focused exercise programs has shown promising results in improving strength and symptoms in adults with patellofemoral pain, but high-quality trials are still scarce[25-27]. Thus, despite accumulating evidence for BFRT in other knee disorders, its comparative effectiveness versus conventional strengthening alone in non-surgical PFPS, particularly regarding pain, quadriceps and hip abductor strength, proprioception, and dynamic balance, remains underexplored and represents an important knowledge gap in the literature[10,13].

Therefore, the current study's goal was aiming to analyze the effect of adding blood flow restriction training BFRT to strengthening exercise program compared with strengthening exercises alone in management of patients with PFPS[10,27].

Study Design

This research study constituted a double blinded, randomized controlled clinical trial (therapy, Level 1B). It was conducted at the outpatient orthopedic physiotherapy department of Almenshawy General Hospital, Tanta, Egypt, from July 2024 to December 2025.

Randomization and Blinding

Following baseline evaluation, participants underwent random assignment utilizing computer-generated random sequences to one of two intervention groups at a 1:1 allocation ratio (www.randomizer.org)[28]. An independent researcher who was not engaged in enrollment, assessment, or treatment administration constructed opaque, sealed envelopes with sequential numbers to ensure allocation concealment.

A blinded research assistant, who was unaware of group allocation, performed all outcome assessments at baseline, 3 weeks, and 6 weeks. The statistician who analyzed the data was also blinded to group assignment and intervention details. To maintain patient blinding, the control group received sham BFRT by applying an unconnected cuff during the strengthening exercises, while the experimental group received active BFRT with the same device appearance and placement, and the treating therapist was not blinded[10,29].

Participants

Fifty individuals diagnosed with PFPS were recruited from orthopedic outpatient clinics and referred by an orthopedic surgeon with a clinical diagnosis of PFPS. A flow diagram (Figure 1), prepared according to the CONSORT statement, was used to illustrate participant screening, allocation, follow-up, and analysis. Males and females between the ages of 18 and 40 who had a body mass index (BMI) between 18.5 and 29.9 kg/m^2 and who reported non-traumatic onset anterior knee pain lasting longer than two weeks, and who felt pain during at least two functional activities, such as running, jumping, squatting, kneeling, climbing and descending stairs, or extended sitting, were eligible to participate[10,30].

Patients with coexisting knee pathology (such as patellar subluxation or dislocation, patellar tendinopathy, or other causes of anterior knee pain, such as bursitis or fat pad pathology), a history of knee surgery, lower limb

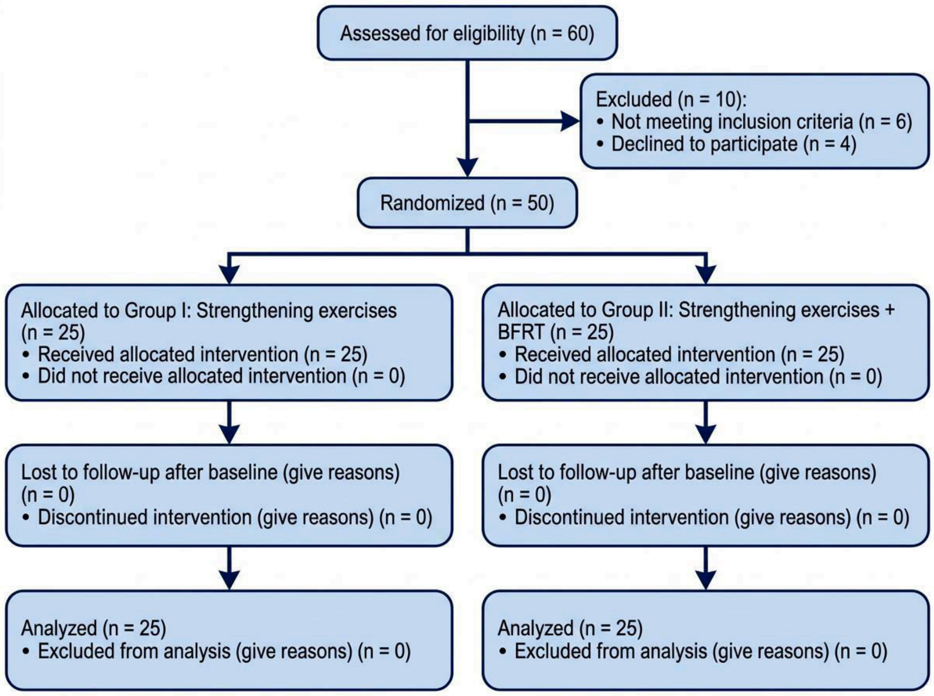

Figure 1. Flow chart diagram.

trauma, hip or ankle pathology, cardiovascular disease, uncontrolled hypertension, BMI greater than 30 kg/m^2, or pregnancy were excluded[10,29,31].

Sample Size Calculation

The sample size was determined a priori using G*Power software (version 3.1.9.2; Franz Faul, Mün Kiel, Germany) using VAS pain information from an earlier PFPS BFRT study[27]. The necessary sample size was 23 people per group, assuming an effect size of 0.85, an alpha level of 0.05, statistical power of 80%, and two groups with repeated measures. The final sample size was established at 25 participants per group (total n = 50) to account for an expected dropout rate of about 10%.

Participant Flow

A total of 60 individuals were screened for eligibility. Of these, 10 participants were excluded prior to randomization, including 6 who did not meet the predefined inclusion criteria and 4 who declined to participate. Consequently, 50 participants were enrolled and randomly assigned in a 1:1 ratio to either Group I (strengthening exercises) or Group II (strengthening exercises combined with BFRT), with 25 participants allocated to each group.

All randomized participants received the allocated intervention as per protocol, and no deviations from the assigned treatment were observed. There were no losses to follow-up after baseline assessment, and no participants discontinued the intervention during the study period.

Accordingly, all randomized participants (n = 50) were included in the final analysis, with complete outcome data available for both groups (n = 25 per group). No participants were excluded from the analysis.

Participant flow throughout the study is presented in Figure 1, in accordance with CONSORT recommendations.

Interventions

All participants underwent supervised treatment consisting of three sessions weekly for six consecutive weeks, delivered by same physical therapist to ensure consistency. Each session lasted approximately 30 - 45 minutes and commenced with a standardized warm-up consists of walking at comfortable speed (3 miles/hour) on a flat surface for 10 minutes, followed by gentle hamstring and calf stretching (3-second holds, 5 repetitions)[32]. All exercises were performed using bodyweight only, with no external weights or resistance bands applied. The program was performed on the affected limb only, while the unaffected limb was not exercised, and no-load progression was used; instead, progression was achieved by completing the scheduled supervised sessions while

Figure 2. Isometric knee exercises. Arrow refers to a sham BFRT applied by placing an uninflated cuff.

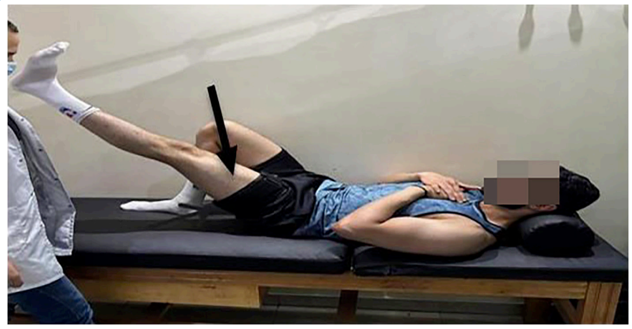

Figure 3. Straight leg raises (SLR) exercises. Arrow refers to a sham BFRT applied by placing an uninflated cuff.

maintaining proper exercise form. Each exercise was performed for 20 repetitions across 3 sets, with 30 seconds of rest between sets, and all 50 participants completed the full 18 supervised sessions, resulting in 100% adherence as recorded in the session attendance logs.

Group I: Strengthening Exercises

Participants in Group I (Strengthening group) performed a standardized lower-limb strengthening program adapted from previous PFPS protocols[33,34]. 20 repetitions × 3 sets with 30 seconds rest between sets. Exercises included:

1. Isometric quadriceps contractions: Supine positioning with a cylindrical roll positioned beneath the knee; participants applied downward pressure against the roll to achieve isometric quadriceps contraction sustained for 5 seconds (Figure 2).

2. Straight leg raise (SLR): Supine position, hip maintained in neutral, knee in full extension, ankle dorsiflexed; participants elevated the limb to approximately 45° hip flexion and performed controlled lowering (Figure 3).

3. Short arc knee extension: Supine with cylindrical roll positioned beneath the knee; participants performed knee extension from flexed position to complete extension and returned (Figure 4).

4. Side lying hip abduction: Side-lying position with trunk in neutral alignment and contralateral limb flexed for stabilization; tested limb positioned with neutral hip rotation and knee extended, performing hip abduction [35] (Figutr 5).

NB: Sham BFRT applied by placing an uninflated cuff on the proximal thigh during exercises without applying occlusive pressure[29].

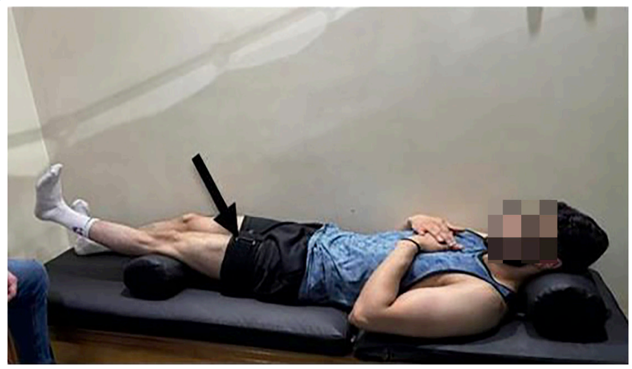

Figure 4. Short arc knee extension exercise. Arrow refers to a sham BFRT applied by placing an uninflated cuff.

Figure 5. Hip abduction from side lying exercise. Arrow refers to a sham BFRT applied by placing an uninflated cuff.

Figure 6. HHD assessment of Quadriceps muscle strength.

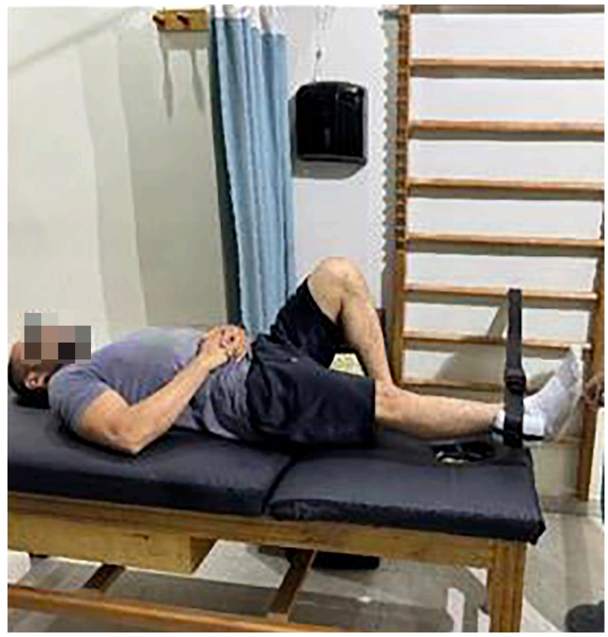

Figure 7. HHD application of Hip abduction strength.

Group II: Strengthening Exercises with Blood Flow Restriction

Group II (BFRT group) performed the same strengthening program and warm-up as Group I, with the addition of active BFRT applied to the trained limb. A SmartCuffs® 3.0 PRO apparatus (SmartTools, USA), designated as an FDA Class I pneumatic tourniquet system, served to determine limb occlusion pressure (LOP) and deliver BFRT[13,36].

Cuff positioning was directly distal to the gluteal fold on the proximal thigh. Individualized LOP underwent automatic establishment by the device using pulsatile pressure increases until arterial flow attenuation was detected. Throughout exercise execution, cuff pressure was maintained at 60% of LOP, a level commonly employed in lower-limb BFRT protocols to balance efficacy and safety. As device recommendations the cuff was deflated during rest intervals and kept inflated during each workout set. All patients were monitored for discomfort, paresthesia, or adverse events, and no serious complications were observed.

Adherence/Compliance

All 50 participants attended the full treatment schedule, resulting in 100% adherence/compliance. Interruption due to intolerance was temporary and did not result in session non-completion or study withdrawal.

Outcome Measures and Instrumentations

The same blinded assessor collected all outcome measures at baseline (pre-treatment), three weeks later (Post I), and six weeks later (Post II). For quadriceps strength as primary outcome, Pain intensity, hip abductor strength, functional ability, knee joint position sense (JPS), and dynamic balance as secondary outcomes.

For all strength assessment, the Lafayette Manual Muscle Tester calculates torque = force × distance, with force converted to Newtons and then expressed as torque per kilogram bodyweight (Nm/kg) by dividing torque by body mass in kilograms. Strength = (HHD reading in Newtons × lever-arm distance in meters) / bodyweight in kilograms[37].

Quadriceps strength

Isometric quadriceps and hip abductor strength underwent measurement using Lafayette hand held dynamometer (HHD; Lafayette Manual Muscle Tester), which has demonstrated excellent reliability when evaluating hip and knee muscular strength in clinical settings[38-40].

Participants were sitting with their knees and hips bent 90 degrees, hands crossed over their trunk, and stabilization straps applied to minimize compensatory movements[41]. The HHD pad was placed perpendicular to anterior tibia, positioned approximately 5 cm proximal to the lateral malleolus. Participants performed maximal

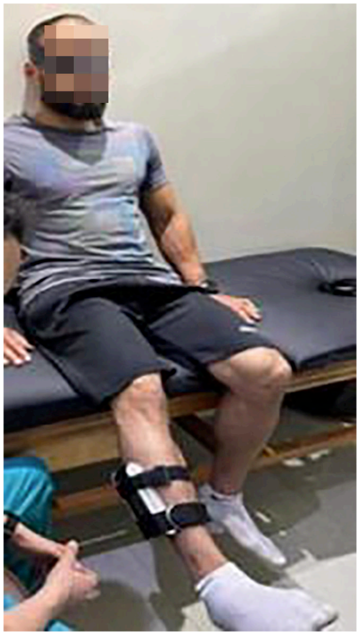

Figure 8. Application of Digital Inclinometer for measuring JPS.

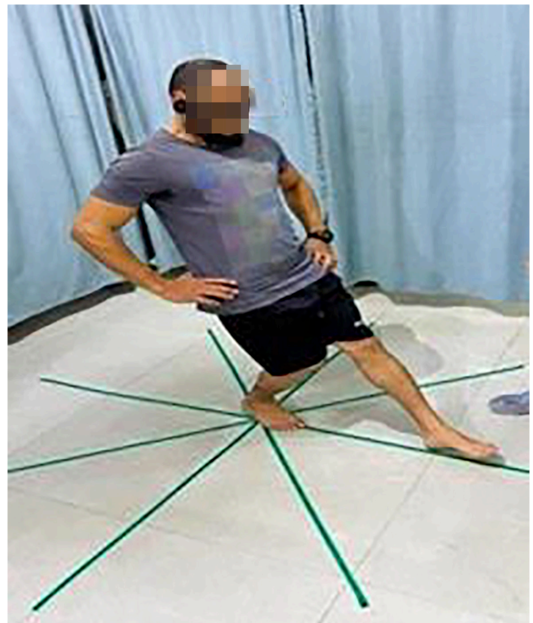

Figure 9. Performance of the Star Excursion Balance Test (SEBT).

isometric knee extension for 5 seconds, with two practice trials and three test trials separated by thirty seconds rest intervals[39] (Figure 6).

Pain

Pain intensity underwent assessment utilizing a 10-cm Visual Analogue Scale (VAS), with terminal anchors designated "no pain" (0 cm) and "worst pain imaginable" (10 cm). The Visual Analogue Scale represents a valid measuring tool to assess pain in patients with PFPS. Participants indicated their current anterior knee pain level, with scores derived by measuring the distance in centimeters from the left anchor to the mark, yielding a 0-10 score where higher values indicated greater pain intensity[43].

Hip abductors Strength

Hip abductor strength underwent measurement using Lafayette hand held dynamometer (HHD; Lafayette Manual Muscle Tester).

Hip abductors strength assessment conducted in supine position, hip and knee extended over table. The HHD was positioned five cm proximal to the lateral malleolus on the lateral leg. A non-elastic belt provided fixed resistance while participants performed maximal isometric hip abduction for five seconds. Three trials were recorded with thirty seconds rest intervals, and mean peak force (kg) was used for analysis[36,41] (Figure 7).

Function

An Arabic version of the KUJALA was used to assess functional limitations and subjective complaints, consists of 13 items covering pain and functional activities, with total scores between 0 (severe disability) and 100 (no symptoms)[42,44,45]. Higher scores represent better function. The Arabic KUJALA score has demonstrated good strong validity and reliability for patients with PFPS[42].

Proprioception

Knee JPS was evaluated using an INSPEC Digital Protractor inclinometer (82201b-00), a device with excellent validity and reliability for open-chain knee JPS assessment[9]. Individuals were positioned seated with both knees and hips flexed to 90° and blindfolded in a calm and quiet environment to minimize visual and auditory cues[46].

From full knee extension, the examiner passively flexed patient's examined knee till a specified target angle (60° flexion) and maintained the position for 5 seconds for three familiarization trials. Participants subsequently received instruction to actively recreate and sustain the target angle. Three test trials were performed, and absolute angular error (difference between target and reproduced angle, in degrees) was calculated as the primary proprioception outcome[9]. Lower error values indicated superior JPS (Figure 8).

Table 1. Demographic and Baseline Subjects characteristics.

	Group I	Group II	MD	t- value	p-value
	Mean ± SD	Mean ± SD			
Age (years)	26.12 ± 4.03	25.84 ± 4.34	0.28	0.24	0.81
Weight (kg)	76.62 ± 9.41	75.35 ± 9.66	1.27	0.47	0.64
Height (cm)	175.72 ± 5.56	175.32 ± 5.13	0.40	0.26	0.79
BMI (kg/m²)	24.81 ± 2.78	24.51 ± 2.97	0.30	0.37	0.72
Sex distribution, N (%)					
Female	10 (40%)	9 (36%)	χ^2 = 0.09		0.77
Male	15 (60%)	16 (64%)			
Affected side, N (%)					
Dominant	19 (76%)	17 (68%)	χ^2 = 0.39		0.53
Non dominant	6 (24%)	8 (32%)			

SD, standard deviation; MD, mean difference; χ^2, Chi squared value; P value, probability value.

Dynamic Balance

The Star Excursion Balance Test (SEBT) was employed to examine and quantify single-leg balance and neuromuscular control across several directions. Four adhesive tape strips were arranged on the floor forming eight reach directions separated by 45° angles. The Star Excursion Balance Test is a reliable assessment tool and a valid for dynamic evaluation to analyzing balance deficits in individuals with lower extremity problems[47,48].

Individuals maintained stance on tested limb at the center of the grid with instruction to reach maximally along each direction (anterior, anteromedial, and anterolateral directions) with the contralateral limb while maintaining balance, applying light touch on tape with big toe, and returning to the initial point position without losing control. Choosing the three directions as they are most often emphasized in PFPS-related postural-control studies and are the directions most relevant to the altered performance pattern in PFPS[48,49].

Trials were eliminated and conducted again if the stance foot moved, the heel lifted, or weight was placed on the reaching limb. Reach distances measured in centimeters (cm), normalized to limb length, and expressed as a percentage (%) of limb length[46] (Figure 9).

Adverse events

Adverse events were monitored throughout the intervention period and recorded after each session. Reported events included transient knee pain, paresthesia that resolved after cuff deflation, bruising at the cuff site, dizziness during exercise, and session interruption temporary due to intolerance. No serious complications, including deep vein thrombosis or nerve injury, were observed.

Statistical Analysis

Normal distribution of data was checked using the Shapiro-Wilk test. Levene's test was conducted to test the homogeneity between groups. Unpaired t test was conducted for comparison of subject characteristics between groups. Chi squared test was conducted for comparison of sex and affected side distribution between groups. Mixed MANOVA was performed to compare within and between groups effects on Quadriceps strength, VAS, Hip abductor strength, KUJALA score, JPS, and SEBT reach distances. Multiple post-hoc tests were conducted using Bonferroni correction. All randomized participants (n = 50) completed the follow-up assessment, and no post-baseline outcome data were missing. Therefore, all analyses were conducted on the full randomized sample, with no participant exclusions. The level of significance was set at $p < 0.05$. All statistical analysis was conducted through the Statistical Package for Social Sciences (SPSS) version 25 for windows (IBM SPSS, Chicago, IL, USA).

Results

Subject characteristics

Fifty individuals with PFPS completed the study and underwent analysis (25 individuals in the strengthening exercise group and 25 individuals in the BFRT group). Table 1 shows the subject characteristics of group I and II. There was no significant difference in age, weight, height, BMI and sex and affected side distribution between groups ($p > 0.05$). (Table 1).

Some adverse events were reported throughout the study as mentioned in (Table 2).

Table 2. The adverse events reported during the intervention period.

Adverse Event	BFRT Group (n=25)	Strengthening Group (n=25)
Increased knee pain (transient, <24h)	4 (16%)	3 (12%)
Paresthesia (tingling, resolved with cuff deflation)	2 (8%)	0 (0%)
Bruising at cuff site	3 (12%)	0 (0%)
Dizziness during exercise	1 (4%)	0 (0%)
Session interruption due to intolerance	1 (4%)	0 (0%)
Serious complications (DVT, nerve injury, etc.)	0 (0%)	0 (0%)

NB: interruption due to intolerance was temporary and did not result in session non-completion or study withdrawal. Therefore, adherence and compliance remained 100% throughout the intervention period.

Table 3. Comparison of Quadriceps Strength, Pain, Hip abductors Strength, KUJALA, JPS, and SEBT between pre-treatment, Post I and Post II for group I.

Outcome	Pre-treatment vs Post I			Pre-treatment vs Post II			Post I vs Post II		
	MD	95% CI	p-value	MD	95% CI	p-value	MD	95% CI	p-value
Quadriceps strength (Nm/kg)	-0.09	-0.16: -0.02	0.01	-0.2	-0.31: -0.08	0.001	-0.11	-0.16: -0.05	0.001
VAS	2.55	2.25: 2.85	0.001	3.79	3.43: 4.16	0.001	1.24	0.91: 1.58	0.001
Hip abductors strength (Nm/kg)	-0.1	-0.15: -0.05	0.001	-0.15	-0.22: -0.08	0.001	-0.05	-0.08: -0.02	0.002
KUJALA	-30.36	-33.94: -26.78	0.001	-41.52	-45.34: -37.70	0.001	-11.16	-13.85: -8.47	0.001
JPS (degrees)	0.68	0.39: 0.97	0.001	2.06	1.54: 2.58	0.001	1.38	1.01: 1.75	0.001
SEBT (% of leg length)									
Anterior SEBT	-5.88	-6.61: -5.15	0.001	-13.42	-14.33: -12.52	0.001	-7.54	-8.36: -6.72	0.001
Anteromedial SEBT	-10.72	-12.71: -8.73	0.001	-17.69	-19.21: -16.16	0.001	-6.97	-8.58: -5.36	0.001
Anterolateral SEBT	-2.44	-3.58: -1.29	0.001	-13.46	-14.68: -12.23	0.001	-11.02	-11.86: -10.18	0.001

MD, mean difference; CI, confidence interval; p-value, probability value; p value, probability value.

Effect of treatment on Quadriceps Strength, VAS, Hip abductors Strength, KUJALA, JPS, and SEBT

Mixed MANOVA revealed that there was a significant interaction of treatment and time ($F (16, 33) = 13.23$, $p < 0.001$, $\eta p^2 = 0.87$). There was a significant main effect of time ($F (16, 33) = 1014.77$, $p < 0.001$, $\eta p^2 = 0.99$). There was a significant main effect of group ($F (8, 41) = 2.65$, $p < 0.02$, $\eta p^2 = 0.34$).

Within-Group Comparison

Both groups demonstrated significant improvements in Pain (VAS), quadriceps, hip abductors strength, Function (KUJALA) score, JPS, and SEBT after 3 weeks (post I) ($p < 0.01$). Further significant enhancements emerged after 6 weeks (post II) while compared to both pre-treatment and (Post I) ($p < 0.01$) (Tables 3 and 4).

Between-Group Comparison Baseline

At baseline, there were no significant differences between groups in quadriceps and hip abductor strength, VAS, KUJALA, JPS, or SEBT scores ($p > 0.05$).

At Post I, group II had significant greater improvement than group I in quadriceps strength, hip abductor strength, and VAS ($p < 0.05$), with moderate effect sizes (ηp^2 = 0.115, 0.089, and 0.209, respectively). While there was no significant difference between groups in KUJALA, JPS, and all SEBT directions at post I ($p > 0.05$).

At Post II, group II had significant greater improvement compared with group I in quadriceps and hip abductor strength, VAS, KUJALA ($p < 0.01$), with large effect sizes (ηp^2 = 0.120: 0.466). However, there were no significant differences between groups in JPS and all SEBT directions at post II ($p > 0.05$). (Table 5).

Table 4. Comparison of Quadriceps Strength, Pain, Hip abductors Strength, KUJALA, JPS, and SEBT between pre-treatment, Post I and Post II for group II.

Outcome	Pre-treatment vs Post I			Pre-treatment vs Post II			Post I vs Post II		
	MD	95% CI	p-value	MD	95% CI	p-value	MD	95% CI	p-value
Quadriceps strength (Nm/kg)	-0.42	-0.49: -0.34	0.001	-0.58	-0.70: -0.47	0.001	-0.16	-0.22: -0.11	0.001
Hip abductors strength (Nm/kg)	-0.27	-0.32: -0.23	0.001	-0.4	-0.47: -0.33	0.001	-0.13	-0.16: -0.09	0.001
VAS	3.1	2.80: 3.40	0.001	4.85	4.49: 5.21	0.001	1.75	1.41: 2.08	0.001
KUJALA	-33.56	-37.14: -29.98	0.001	-49.20	-53.02: -45.38	0.001	-15.64	-18.33: -12.95	0.001
JPS (degrees)	0.78	0.49: 1.07	0.001	2.12	1.60: 2.64	0.001	1.34	0.97: 1.71	0.001
SEBT (% of leg length)									
Anterior SEBT	-8.11	-8.84: -7.38	0.001	-16.56	-17.47: -15.66	0.001	-8.45	-9.27: -7.63	0.001
Anteromedial SEBT	-12.98	-14.96: -10.98	0.001	-19.42	-20.94: -17.89	0.001	-6.44	-8.06: -4.84	0.001
Anterolateral SEBT	-4.01	-5.15: -2.87	0.001	-14.95	-16.17: -13.73	0.001	-10.94	-11.78: -10.10	0.001

MD, mean difference; CI, confidence interval; p-value, probability value; p value, probability value.

Table 5. Comparison of Quadriceps Strength, Pain, Hip abductors Strength, KUJALA, JPS, and SEBT between groups.

Outcomes		Group I	Group II	MD	95% CI	p-value	ηp^2
		Mean ± SD	Mean ± SD				
Quadriceps strength (Nm/kg)	Pre-treatment	1.14 ± 0.55	1.21 ± 0.43	-0.07	-0.34: 0.22	0.65	0.004
	Post I	1.23 ± 0.57	1.63 ± 0.54	-0.4	-0.71: -0.08	0.01	0.115
	Post II	1.34 ± 0.62	1.79 ± 0.64	-0.45	-0.81: -0.10	0.01	0.120
VAS	Pre-treatment	7.12 ± 0.65	7.07 ± 0.80	0.05	-0.36: 0.47	0.80	0.001
	Post I	4.57 ± 0.47	3.97 ± 0.71	0.60	0.26: 0.95	0.001	0.209
	Post II	3.33 ± 0.59	2.22 ± 0.62	1.11	0.76: 1.45	0.001	0.466
Hip abductors strength (Nm/kg)	Pre-treatment	1.02 ± 0.32	1.08 ± 0.31	-0.06	-0.24: 0.12	0.53	0.008
	Post I	1.12 ± 0.35	1.35 ± 0.41	-0.23	-0.45: -0.02	0.03	0.089
	Post II	1.17 ± 0.36	1.48 ± 0.46	-0.31	-0.55: -0.08	0.01	0.130
KUJALA	Pre-treatment	37.52 ± 7.64	37.76 ± 7.87	-0.24	-4.65: 4.17	0.91	0.001
	Post I	67.88 ± 8.72	71.32 ± 6.91	-3.44	-7.91: 1.03	0.13	0.047
	Post II	79.04 ± 9.62	86.96 ± 6.54	-7.92	-12.60: -3.24	0.001	0.195
JPS (degrees)	Pre-treatment	7.96 ± 1.77	7.98 ± 1.84	-0.02	-1.05: 1.01	0.97	0.001
	Post I	7.28 ± 1.45	7.20 ± 1.68	0.08	-0.81: 0.97	0.86	0.001
	Post II	5.90 ± 1.08	5.86 ± 1.29	0.04	-0.64: 0.72	0.91	0.001
SEBT (% of leg length)							
Anterior SEBT	Pre-treatment	73.63 ± 4.37	72.07 ± 3.01	1.56	-0.57: 3.69	0.15	0.043
	Post I	79.51 ± 4.09	80.18 ± 3.43	-0.67	-2.82: 1.48	0.53	0.008
	Post II	87.05 ± 5.41	88.63 ± 3.81	-1.58	-4.24: 1.08	0.24	0.029
Anteromedial SEBT	Pre-treatment	61.41 ± 2.61	60.67 ± 2.39	0.74	-0.68: 2.16	0.30	0.022
	Post I	72.13 ± 3.87	73.65 ± 3.71	-1.52	-3.67: 0.64	0.16	0.04
	Post II	79.10 ± 3.18	80.09 ± 2.52	-0.99	-2.63: 0.64	0.23	0.03
Anterolateral SEBT	Pre-treatment	47.14 ± 3.23	46.92 ± 2.43	0.22	-1.40: 1.85	0.78	0.002
	Post I	49.58 ± 3.07	50.93 ± 2.76	-1.35	-3.01: 0.31	0.11	0.053
	Post II	60.60 ± 3.67	61.87 ± 3.14	-1.27	-3.21: 0.67	0.19	0.035

SD, standard deviation; MD, mean difference; CI, confidence interval; p-value, probability value; ηp^2, Partial Eta Squared.

Discussion

The current research study was structured to compare effects of incorporating blood flow restriction training (BFRT) combined with strengthening exercises versus the same strengthening exercises alone on pain, function, strength, joint position sense, and dynamic balance in individuals with PFPS.

Study outcomes indicated that both groups exhibited significant improvements across all outcome measures at all assessment points. Between-group analyses of pain and strength revealed significantly greater improvement in the BFRT group compared to the strengthening group after three weeks and also after six weeks. Function after three weeks revealed no significant difference between groups; however, after six weeks the BFRT group displayed significantly elevated scores. Joint Position Sense (JPS) and Star Excursion Balance Test (SEBT) showed no difference between both groups at all assessment points.

Pain and Strength

The superior pain reduction in the BFRT group may be attributed to conditioned pain modulation mechanisms, where ischemia and pressure-induced muscle pain serve as conditioning stimuli to activate endogenous inhibitory pathways, thereby decreasing pain sensitivity[23]. Similarly, the combination of compression cuff pressure, local ischemia, and exercise-induced muscle pain during BFRT may activate descending inhibitory systems and thereby contribute to post-exercise analgesia[20,21]. Additionally, other postulated mechanisms include the release of endogenously produced substances with anti-nociceptive effects during exercise[24]. For instance, research has shown that BFRT can increase beta-endorphin levels and reduce pain sensitivity for up to 24 hours after exercise[22].

Furthermore, the present findings are supported by Li et al.[25], who reported that pain scores were significantly lower in the low-load BFRT group compared with high-load resistance training in patients with knee osteoarthritis. Similarly, Giles et al.[10] demonstrated that low-load resistance exercise with BFRT significantly reduced pain in individuals with PFPS when compared to baseline values. These observations align with our results, demonstrating progressive pain reduction in both groups with significantly greater improvements in the BFRT group at both 3 and 6 weeks of intervention.

Significant improvement of quadriceps strength in BFRT group demonstrating substantially greater gains. This observation carries clinical significance given that quadriceps weakness represents one of the most consistent impairments in PFPS and is strongly associated with pain severity, functional limitation, and disease progression[4,5]. The superior strength gains in the BFRT group, despite utilizing lower training loads, suggest that the metabolic stress and cellular swelling induced by blood flow restriction provide a potent stimulus for muscle hypertrophy and strength development.

These findings are consistent with those of Slysz et al.[13] and Abe et al.[14], who demonstrated that BFRT combined with low-load resistance exercise produces muscular adaptations similar to high-load training by increasing systemic lactate, calcium, muscle-derived myokines, and blood acidity. In the context of PFPS, Scott et al.[50] showed that BFRT significantly improved quadriceps strength in patients following anterior cruciate ligament reconstruction, while Giles et al.[10] reported similar findings in individuals with PFPS.

The clinical advantage of BFRT lies in its ability to achieve these strength gains, thereby minimizing patellofemoral joint stress and reducing the risk of pain exacerbation during training[19,51]. This makes BFRT particularly suitable for pain-limited populations such as those with PFPS, where traditional high-load strengthening may not be well tolerated.

Hip abductors weakness always identifies as a key impairment in PFPS, contributing to excessive femoral internal rotation and adduction during dynamic tasks, which increases patellofemoral joint stress and perpetuates anterior knee pain[12,52]. Therefore, the superior hip abductor strength gains in the BFRT group may translate to improved kinematic control and reduced abnormal loading patterns at the patellofemoral joint.

These findings are supported by Sled et al.[11] and Hewidy et al.[35], who demonstrated that hip abductor strengthening exercises significantly reduced pain and improved function in patients with PFPS. The addition of BFRT in this study appeared to deliver greater short term improvements in pain, strength, and function[18]. Moreover, Ferlito et al.[53] and Bobes et al.[54] reported that BFRT combined with resistance training produced superior strength gains in patients with knee osteoarthritis, a condition that shares similar biomechanical impairments with PFPS.

Function (KUJALA) Score

The BFRT group exhibited a significant greater improvement in KUJALA scores at six weeks post-intervention assessment relative to the strengthening group, suggesting that the addition of BFRT not only enhances pain and strength outcomes but also translates to better functional performance and quality of life. This carries clinical meaning because functional capacity represents a primary concern for patients with PFPS, many of whom experience difficulty with daily living activities such as stair climbing, squatting, and prolonged sitting[40].

The superior functional gains in the BFRT group may stem from the combined effects of greater pain reduction and muscle strength improvement, both of which facilitate better movement patterns and increased confidence during functional tasks. These findings are consistent with those of Kumar et al.[34] and Fukuda et al.[33], who reported significant improvements in KUJALA scores following strengthening exercise programs in patients with PFPS. The addition of

BFRT appears to enhance these outcomes by providing a more efficient training stimulus that maximizes muscle adaptation while minimizing joint stress.

Joint Position Sense (JPS) and Star Excursion Balance Test (SEBT)

Joint Position Sense (JPS) and Star Excursion Balance Test (SEBT) improved within both groups, with absence of between-group differences at either 3 weeks or 6 weeks, which indicates that the BFRT group did not confer an additional proprioceptive benefit or dynamic balance benefit beyond that obtained with conventional strengthening.

From a clinical perspective, these findings indicate that while BFRT may enhance pain, strength and function outcomes, improvements in JPS or SEBT appear to be primarily driven by the general exercise program, and not specifically augmented by BFRT.

Kaya et al.[8] examined the relationship between pain at the patellofemoral joint and proprioception deficit, suggesting that tension and pressure caused by patellofemoral joint malalignment led to alteration of proprioceptive information. Similarly, Romero-Franco et al.[9] demonstrated that digital inclinometer valid and reliable tool to assess knee proprioception through JPS in open kinetic chain exercises. However, Çiçek and Çolak[55] found no statistically significant between-group differences in knee joint position sense values in individuals with PFPS, indicating that improvements in pain and function are not always accompanied by measurable changes in JPS. These findings are remain consistent with the present study, where both groups showed time-dependent improvements in JPS but no additional benefit of BFRT over strengthening.

In support of our observations, Kochar et al.[56] reported that both isometric exercise and somatosensory training protocols significantly improved proprioception and balance in individuals with PFPS. This reinforces the concept that targeted neuromuscular and sensory-focused interventions can enhance dynamic stability, aligning with the improvements in SEBT performance observed in both groups in the present study. Additionally, Goto et al.[57] compared lower-extremity muscle activity, pain level, kinematics, and anterior reach distance during the SEBT between participants with PFPS and healthy controls. They identified altered muscle activation patterns in the PFPS group, characterized by relative overactivity of the adductor longus compared with the gluteus medius during the anterior reach, indicating a distinctive and less efficient neural recruitment strategy in individuals with PFPS. These findings underscore the importance of targeting hip musculature and movement control in rehabilitation to normalize muscle recruitment during dynamic balance tasks, which is consistent with the focus of the present study on strengthening hip abductors and improving functional stability.

Clinical Implications

The findings of this investigation suggest potential clinical implications that warrant further study. However, given the preliminary nature of the evidence, clinicians should consider BFRT as an optional adjunct on a case by case basis until larger trials confirm these results. Preliminary evidence suggests that the addition of BFRT to strengthening exercises may result in more favorable outcomes on pain, strength, and function. These benefits are achieved while utilizing lower training loads, which minimizes patellofemoral joint stress and makes the intervention suitable for pain-limited populations. Preliminary findings suggest that clinicians may explore the potential role of BFRT in rehabilitation protocols for patients with PFPS, although further evidence is needed to support routine clinical implications. However, it is important to note that BFRT did not provide additional benefits for proprioception (JPS) or dynamic balance (SEBT) beyond those achieved with strengthening exercises group. Therefore, rehabilitation programs may preliminarily include both BFRT for pain, strength and function outcomes, as well as neuromuscular and balance-focused exercises to address all impairments associated with PFPS comprehensively.

Limitations

This study has several limitations. First, it was conducted at a single center with a relatively small sample size (n = 50) for a multi-outcome repeated-measures trial, which may limit generalizability and increase the risk of type II error for secondary outcomes (e.g., SEBT, JPS).

Second, the absence of a true placebo or attention control group precludes fully excluding contributions from additional therapist interaction or session time in the BFRT arm.

Third, the 6-week follow-up period may not capture long-term sustainability of improvements; future studies should include extended periods (e.g., 3-6 months). We also did not assess physical activity levels, return-to-sport outcomes, or adherence beyond supervised sessions, where compliance was 100% but may not reflect real-world settings.

Fourth, biomechanical variables (e.g., knee kinematics, hip/knee moments) were not measured, limiting insights into underlying mechanisms.

Fifth, the BFRT protocol used a fixed pressure of 60% limb occlusion pressure (LOP), and optimal parameters (e.g., individualized pressure, volume, and frequency) require further investigation. Sixth, participants were aged 18-40 years with non-traumatic patellofemoral pain syndrome (PFPS); results may not generalize to other ages or traumatic knee injuries.

Seventh, the treating therapist was not blinded to group allocation because the same therapist deliverd both the BFRT and sham BFRT interventions. Although outcome assessors, participants, and the statistician were blinded, therapist non-blinding may have introduced performance bias and should be considered when interpreting the findings.

Finally, although quadriceps strength was designated as the primary outcome during the manuscript preparation, it was not prospectively specified in the original trial registration. Thus, this should be considered when interpreting the study findings.

Conclusion

This study provides preliminary evidence supporting the addition of blood flow restriction training to strengthening exercises in individuals with PFPS over a 6-week intervention period, particularly for enhancing quadriceps strength, reducing pain, and improving hip abductor strength and function. However, given the short follow-up duration, small sample size, and the absence of additional benefits for proprioception and dynamic balance, these findings should be considered preliminary.

Ethics Approval

The study was approved by the Ethics Committee of the Faculty of Physical Therapy, Cairo University (Approval No: P.T.REC/012/005148). The study was conducted in accordance with the ethical principles of the Declaration of Helsinki 1964 and its later amendments.

Consent to Participate

Written informed consent was obtained from all participants before enrolment in the study.

Authors' Contributions

Abdelrahman Hewidy: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Visualization, Project administration, Corresponding author. Enas Youssef: Conceptualization, Methodology, Supervision, Writing - review & editing. Ahmed Khalil: Data curation, Formal analysis, Investigation, Writing - review & editing. Ahmed Helal: Resources, Funding acquisition, Writing - review & editing. Abdelgalil Abdelgalil: Supervision, Writing - review & editing. All authors read and approved the final version of the manuscript.

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