

RESEARCH PAPER

Effectiveness of low-load blood flow restriction training as an adjunct to conventional physiotherapy after total knee replacement: a randomised controlled trial

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ABSTRACT

Background: Quadriceps weakness persists after total knee replacement (TKR), and high-load strengthening is poorly tolerated early after surgery. Low-load blood flow restriction (BFR) training may strengthen muscle with less joint loading.

Objective: To compare BFR training plus conventional physiotherapy with conventional physiotherapy alone after primary unilateral TKR.

Methods: In this assessor-blinded randomised controlled trial, 60 patients aged 45–75 years, 1–4 weeks after TKR, were allocated to BFR plus conventional physiotherapy (n = 30) or conventional physiotherapy alone (n = 30), three supervised sessions weekly for six to eight weeks. BFR exercise used 20–30% of one-repetition maximum at 80% limb occlusion pressure. Outcomes were isometric quadriceps strength, Timed Up and Go (TUG), Six-Minute Walk Test (6MWT) and Numeric Pain Rating Scale (NPRS).

Results: All participants completed the trial, and both groups improved on every outcome ($p < 0.001$). The BFR group improved more in quadriceps strength (between-group difference in change 13.2 Nm; 95% CI 11.9 to 14.6), TUG (–3.7 s; –4.1 to –3.3), 6MWT (60.5 m; 53.5 to 67.5) and pain (–1.6 points; –2.3 to –1.0); all $p < 0.001$. No adverse events were recorded.

Conclusion: Adding low-load BFR training to conventional physiotherapy after TKR produced greater short-term gains in strength, mobility, walking endurance and pain than conventional physiotherapy alone. Larger trials with longer follow-up are needed.

Keywords: Blood flow restriction therapy; Total knee arthroplasty; Quadriceps muscle; Rehabilitation; Resistance training; Physical therapy modalities

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INTRODUCTION

Total knee replacement (TKR) is an established treatment for end-stage knee osteoarthritis and other degenerative knee conditions, and it reliably relieves pain and corrects deformity. Restoration of physical function, however, is often incomplete. Quadriceps weakness is one of the most consistent impairments after TKR and is more strongly related to functional performance than knee range of motion or pain (Mizner et al., 2005a). Strength declines sharply in the first postoperative month, driven by both muscle atrophy and failure of voluntary muscle activation (Mizner et al., 2005b), and deficits can persist despite rehabilitation.

Progressive resistance training is central to restoring quadriceps strength, but conventional recommendations for strength and hypertrophy rely on moderate to high external loads. In the early weeks after TKR, pain, effusion, limited range of motion and concern for the healing joint frequently prevent patients from tolerating such loads (Hughes et al., 2017; Patterson et al., 2019). Clinicians therefore face a practical dilemma: the loads that are safe may be too low to produce meaningful adaptation, while the loads that are effective may not be tolerated.

Blood flow restriction (BFR) training offers a possible solution. A pneumatic cuff applied to the

proximal limb partially restricts arterial inflow and occludes venous outflow during low-load exercise, typically at 20–30% of one-repetition maximum (1RM). The resulting local hypoxia and metabolic stress increase recruitment of higher-threshold motor units and stimulate adaptations in strength and muscle size that approach those of heavy-load training (Patterson et al., 2019; De Renty et al., 2023). A meta-analysis in clinical musculoskeletal populations found low-load BFR training to be more effective than low-load training alone and better tolerated than heavy-load training (Hughes et al., 2017). When patients are appropriately screened and pressure is individualised, the approach appears safe (Patterson et al., 2019; Nascimento et al., 2022). Evidence specific to TKR is still limited and has focused mainly on the preoperative period. Randomised trials of BFR prehabilitation have reported feasibility and some strength benefits, but inconsistent effects on postoperative function (Jørgensen et al., 2024; Kubo et al., 2024; Przkora et al., 2021; Franz et al., 2022). Recent systematic reviews conclude that BFR is promising in knee arthroplasty but that trials are few, small and heterogeneous, and that postoperative applications are under-studied (Tiss et al., 2025; Chen et al., 2025). Early postoperative studies, including passive BFR during hospital stay (Franz et al., 2025) and a case-control study of BFR added to standard rehabilitation (Giusti et al., 2026), suggest benefits for muscle preservation, strength and mobility, but randomised evidence for active low-load BFR exercise during outpatient rehabilitation remains scarce, and no trials from India were identified. This study therefore aimed to evaluate whether adding low-load BFR training to conventional physiotherapy improves quadriceps strength, functional mobility, walking endurance and pain more than conventional physiotherapy alone in patients recovering from primary unilateral TKR. We hypothesised that the BFR group would show greater improvement in all four outcomes.

METHODS

Study design and ethics

This was a single-centre, parallel-group, assessor-blinded randomised controlled trial with a 1:1 allocation ratio, conducted in the inpatient and outpatient physiotherapy departments of a tertiary care orthopaedic hospital and rehabilitation centre in Ghaziabad, India. The protocol was approved by the Institutional Ethics Committee of the Institute of Applied Medicines and Research, Ghaziabad. The study was conducted in accordance with the Declaration of Helsinki. All participants gave written informed consent before enrolment. The trial is reported following the CONSORT 2025 statement (Hopewell et al., 2025).

Participants

Consecutive patients attending the physiotherapy departments after primary unilateral TKR were screened. Inclusion criteria were age 45–75 years; either sex; 1–4 weeks after surgery; medical stability with clearance from the operating orthopaedic surgeon for physiotherapy; and ability to understand and follow exercise instructions. Exclusion criteria were revision or bilateral TKR; severe cardiovascular disease or uncontrolled hypertension; history or evidence of deep vein thrombosis or peripheral vascular disease; uncontrolled diabetes, severe peripheral neuropathy or vascular complications; active infection, unhealed wound or recent fracture of the operated limb; neurological or psychiatric disorders affecting participation; and inability or unwillingness to comply with the rehabilitation protocol. Screening for BFR contraindications followed published risk-stratification recommendations (Nascimento et al., 2022).

Sample size

The sample size was calculated for the primary outcome, quadriceps strength, using a two-sided α of 0.05, power of 80% and an anticipated large effect size (Cohen's $d = 0.8$) based on previous BFR literature. This required 25 participants per group. Allowing for 10–15% attrition, 30 participants per group (60 in total) were recruited.

Randomisation, allocation concealment and blinding

After baseline assessment, participants were randomly allocated to the experimental or control group using a computer-generated random sequence. Allocation was concealed using sequentially numbered, sealed, opaque envelopes opened by a person not involved in recruitment or outcome assessment. The outcome assessor was blinded to group allocation. Because of the nature of the intervention, participants and treating physiotherapists could not be blinded.

Interventions

Both groups attended supervised physiotherapy sessions three times a week for six to eight weeks; each session lasted 45–60 minutes, and therapist contact time was matched between groups. All sessions were delivered by a qualified physiotherapist. Exercise progression in both groups was based on pain not exceeding 3/10 on the NPRS and the absence of increased swelling or adverse symptoms. The phase-wise protocol is summarised in Table 1.

Experimental group (BFR + conventional physiotherapy). BFR was applied using a pneumatic cuff placed around the proximal thigh of the operated limb. Limb occlusion pressure (LOP) was measured individually before training, and cuff pressure during exercise was set at 80% of LOP. Exercises were performed at 20–30% of 1RM (or with minimal resistance in the early phase) using four sets of 30, 15, 15 and 15 repetitions, with 30–45 s rest between

sets while the cuff remained inflated. The cuff was deflated for 1–2 min between exercises. In weeks 1–2, exercises comprised quadriceps sets, straight leg raises, short-arc quadriceps, heel slides and sit-to-stand from a high chair; in weeks 3–4, seated knee extension within a protected range, mini-squats, step-ups (10–15 cm) and partial-range leg press; and from week 5 onwards, sit-to-stand from a standard chair, step-ups (15–20 cm), leg press through a greater range and functional strengthening at 25–30% 1RM. Participants also received the conventional programme described below. Vital signs and limb sensation were monitored throughout, and BFR was stopped immediately for excessive pain, dizziness, numbness or discomfort.

Control group (conventional physiotherapy alone). Participants received a standard progressive programme without BFR, consisting of pain management, active and assisted range-of-motion exercises, quadriceps sets, straight leg raises, heel slides, ankle pumps, and gait training with progressive weaning from assistive devices. Strengthening progressed from body weight or very low resistance (2–3 sets of 10–15 repetitions) in weeks 1–2, to knee extension, mini-squats, step-ups and sit-to-stand at 40–60% 1RM (3 sets of 8–12 repetitions) in weeks 3–4, and to leg press, lunges, stair climbing and walking endurance training at 50–70% 1RM (3–4 sets of 8–12 repetitions) thereafter, with 60–90 s rest between sets. Balance, proprioceptive and functional task training were included throughout.

Outcome measures

Outcomes were measured at baseline and at the end of the intervention period by the same blinded assessor using standardised procedures. The primary outcome was isometric quadriceps strength of the operated limb, recorded as peak torque (Nm) during a maximal voluntary isometric knee extension in sitting with hip and knee flexed to 90°, using an isometric dynamometer. Secondary outcomes were functional mobility, measured with the Timed Up and Go (TUG) test (time in seconds to rise from a standard chair, walk 3 m, turn, return and sit down); walking endurance, measured with the Six-Minute Walk Test (6MWT; distance in metres walked at a self-selected pace along a marked corridor); and pain intensity during activity, rated on the 0–10 Numeric Pain Rating Scale (NPRS). Adverse events and session attendance were recorded at every session.

Statistical analysis

Data were analysed using standard statistical software on an intention-to-treat basis; as no participant withdrew, all randomised participants were analysed in their allocated groups. Continuous variables are presented as mean $\pm$ standard deviation (SD) and categorical variables as frequencies. Normality was examined with the Shapiro–Wilk test and homogeneity of variance with Levene’s test.

Baseline characteristics were compared using independent t-tests and the chi-square test. Within-group changes were analysed with paired t-tests and are reported as mean change with 95% confidence interval (CI). The primary between-group comparison was the difference in mean change from baseline, analysed with independent t-tests and reported with 95% CIs and Cohen’s d. Because change scores deviated from normality in some variables, results were confirmed with Wilcoxon signed-rank and Mann–Whitney U tests. As a sensitivity analysis, analysis of covariance (ANCOVA) was used to compare post-intervention values between groups with the baseline value as a covariate. Statistical significance was set at $p < 0.05$ (two-sided).

RESULTS

Participant flow and baseline characteristics

Sixty eligible patients were randomised, 30 to each group (Figure 1). All participants received the allocated intervention and completed post-intervention assessment, and all 60 were included in the analysis. Participants were aged 50–75 years (mean 63.3 ± 7.7 years); 31 (52%) were men. The groups were comparable at baseline in age, sex, height, weight and all outcome measures (Table 2).

Primary outcome

Quadriceps strength improved significantly in both groups (Table 3). The mean increase was 26.6 Nm (95% CI 25.6 to 27.6), or 61.6%, in the BFR group and 13.4 Nm (95% CI 12.5 to 14.3), or 31.4%, in the control group. The between-group difference in change was 13.2 Nm (95% CI 11.9 to 14.6; $p < 0.001$; $d = 5.06$) in favour of BFR training (Figure 2A).

Secondary outcomes

TUG time decreased by 6.7 s (95% CI 6.4 to 7.1) in the BFR group and by 3.1 s (95% CI 2.9 to 3.3) in the control group, a between-group difference of -3.7 s (95% CI -4.1 to -3.3 ; $p < 0.001$). Six-minute walk distance increased by 130.0 m (95% CI 124.6 to 135.4) and 69.5 m (95% CI 64.8 to 74.3), respectively, a difference of 60.5 m (95% CI 53.5 to 67.5; $p < 0.001$). Pain decreased by 4.5 points (95% CI 4.1 to 4.9) with BFR and by 2.9 points (95% CI 2.4 to 3.4) with conventional physiotherapy alone, a difference of -1.6 points (95% CI -2.3 to -1.0 ; $p < 0.001$) (Table 3; Figure 2B–D).

All within-group and between-group results were unchanged when non-parametric tests were used (all $p < 0.001$). Baseline-adjusted ANCOVA gave consistent estimates: 13.2 Nm (95% CI 11.8 to 14.6) for quadriceps strength, -3.8 s (-4.1 to -3.4) for TUG, 60.5 m (53.5 to 67.5) for 6MWT and -1.9 points (-2.4 to -1.5) for pain (all $p < 0.001$).

Adverse events

No adverse events, including excessive pain, numbness, vascular complications or cardiovascular instability, were recorded in either group.

DISCUSSION

In this randomised controlled trial, adding low-load BFR training to conventional physiotherapy in the early weeks after primary unilateral TKR produced greater improvements in quadriceps strength, functional mobility, walking endurance and pain than conventional physiotherapy alone. Both groups improved substantially, but the gain in quadriceps strength in the BFR group was roughly twice that of the control group, and similar differences were seen for TUG and 6MWT. These findings were consistent across parametric, non-parametric and baseline-adjusted analyses.

The strength findings are consistent with the physiological rationale for BFR. Restricting blood flow during low-load exercise increases metabolic stress and accelerates fatigue of lower-threshold fibres, which forces recruitment of higher-threshold motor units that would otherwise require heavy loads to activate (Patterson et al., 2019; De Renty et al., 2023). This mechanism is particularly relevant after TKR, where early quadriceps weakness reflects both atrophy and impaired voluntary activation (Mizner et al., 2005b). In our trial, the BFR group trained at 20–30% of 1RM, whereas the control group progressed to 40–70% of 1RM, yet the BFR group gained more strength. This supports the view that BFR can provide an adequate training stimulus while keeping joint loading low during a period when heavier loading is poorly tolerated (Hughes et al., 2017; De Renty et al., 2023).

Our results agree with non-randomised and early postoperative evidence. Giusti et al. reported greater gains in quadriceps strength and functional mobility when BFR was added to postoperative rehabilitation after knee arthroplasty (Giusti et al., 2026), and Franz et al. found that passive BFR started immediately after TKR reduced muscle atrophy and swelling and accelerated recovery of walking endurance (Franz et al., 2025). Beyond arthroplasty, BFR training produced greater strength and pain improvements than traditional weight-bearing exercise in knee osteoarthritis (Hu et al., 2023), and trials and systematic reviews of BFR after knee surgery report strength gains that are comparable to or greater than those of conventional rehabilitation (Tennent et al., 2017; Chen et al., 2025; Kara Kaya & Polat, 2025; Alamri et al., 2026).

The size of the effects in our study, however, is considerably larger than in most previous trials, and this warrants careful interpretation. Prehabilitation trials have reported smaller or inconsistent benefits: Jørgensen et al. found greater lower-limb strength three months after TKR following preoperative BFR training, but no difference in functional performance or patient-reported outcomes (Jørgensen et al., 2024),

and Kubo et al. found no difference in strength outcomes compared with an active low-intensity control (Kubo et al., 2024). In older adults with knee osteoarthritis, Harper et al. found BFR training to be no more effective than moderate-intensity resistance training for strength (Harper et al., 2019). Several factors may explain the larger differences observed here. First, BFR was delivered after surgery, when the potential for recovery is greatest and when conventional loading is most restricted. Second, all sessions were supervised, which may have ensured high training fidelity. Third, the control group's volume and progression differed from those of the BFR group, so differences in training dosage, rather than BFR alone, may have contributed. Finally, participants and therapists were not blinded, and expectation effects may have influenced performance-based and self-reported outcomes. The between-group effect sizes should therefore be regarded as provisional until replicated.

The greater pain reduction in the BFR group is also noteworthy. Low-load BFR exercise has been shown to produce a short-term, localised hypoalgesic effect in people with knee pain (Al-Ogaili et al., 2025), and pain reduction with BFR has been reported in knee osteoarthritis (Hu et al., 2023; Ferraz et al., 2018). Lower pain may in turn have allowed better engagement with the functional components of rehabilitation, contributing to the larger gains in TUG and 6MWT. Because the NPRS is self-reported and participants were aware of their allocation, this finding should be interpreted with particular caution.

No adverse events occurred. This is consistent with systematic reviews reporting no serious adverse events with BFR in knee arthroplasty populations (Tiss et al., 2025; Chen et al., 2025) and with trials showing no adverse changes in coagulation or inflammatory markers (Kubo et al., 2024). Our exclusion of patients with vascular disease, thrombotic history and uncontrolled cardiometabolic conditions, together with individualised cuff pressure and continuous monitoring, likely contributed to this safety profile (Patterson et al., 2019; Nascimento et al., 2022). The results should not be generalised to patients with these conditions.

This study has several strengths, including random allocation with concealment, a blinded assessor, no loss to follow-up, supervised delivery of all sessions and individualised BFR pressure. Its limitations should also be acknowledged. It was a single-centre trial with a modest sample, which limits generalisability. Outcomes were assessed only immediately after the intervention, so the durability of the benefits is unknown. We did not measure knee range of motion, muscle size, patient-reported function (for example, the Knee injury and Osteoarthritis Outcome Score) or quality of life. Training volume and intensity were not matched between groups. Participants and therapists could not be blinded. Future multicentre trials should include

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longer follow-up, patient-reported outcomes, a economic evaluation.
volume-matched or sham-BFR comparator, and

Table 1. Phase-wise intervention protocol

Phase (weeks)	Parameter	BFR + conventional physiotherapy	Conventional physiotherapy alone
Early (1–2)	Exercises	Quadriceps sets, straight leg raise, short-arc quadriceps, heel slides, sit-to-stand (high chair)	Quadriceps sets, straight leg raise, heel slides, ankle pumps, gait training
	Load; volume	Body weight / minimal resistance with BFR; 4 sets (30-15-15-15)	Body weight / very low resistance; 2–3 × 10–15
Strengthening (3–4)	Exercises	Seated knee extension (protected range), mini-squats, step-ups (10–15 cm), partial-range leg press	Knee extension (protected range), mini-squats, step-ups (10–15 cm), sit-to-stand
	Load; volume	20–30% 1RM with BFR; 4 sets (30-15-15-15)	40–60% 1RM; 3 × 8–12
Advanced (5–8)	Exercises	Sit-to-stand (standard chair), step-ups (15–20 cm), leg press (greater range), functional strengthening	Leg press, lunges, stair climbing, walking endurance
	Load; volume	25–30% 1RM with BFR; 4 sets (30-15-15-15)	50–70% 1RM; 3–4 × 8–12
All phases	Rest	30–45 s between sets (cuff inflated); 1–2 min between exercises (cuff deflated)	60–90 s between sets
	Other	Cuff on proximal thigh at 80% LOP; plus conventional ROM, gait, balance and functional training	ROM, gait, balance, proprioceptive and functional training
	Dose	3 sessions/week, 45–60 min	3 sessions/week, 45–60 min

BFR, blood flow restriction; LOP, limb occlusion pressure; 1RM, one-repetition maximum; ROM, range of motion. Progression in both groups required pain ≤ 3/10 and no increase in swelling.

Table 2. Baseline characteristics of participants

Characteristic	BFR + CP (n = 30)	CP alone (n = 30)	p-value
Age, years	62.80 ± 8.34	63.83 ± 7.15	0.608
Sex, male/female, n	17/13	14/16	0.438
Height, cm	162.73 ± 7.25	164.27 ± 8.37	0.451
Weight, kg	68.70 ± 9.55	65.83 ± 9.46	0.248
Quadriceps strength, Nm	43.15 ± 2.57	42.58 ± 3.11	0.437
Timed Up and Go, s	19.44 ± 1.71	18.72 ± 1.57	0.097
Six-Minute Walk Test, m	281.77 ± 23.04	281.40 ± 21.68	0.950
Pain, NPRS (0–10)	6.70 ± 0.79	6.97 ± 0.89	0.226

Values are mean ± SD unless stated. p-values from independent t-tests, except sex (chi-square test). BFR, blood flow restriction; CP, conventional physiotherapy; NPRS, Numeric Pain Rating Scale.

Table 3. Within-group and between-group changes in outcome measures

Outcome	BFR + CP (n = 30)	CP alone (n = 30)
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	Baseline	Post	Change (95% CI)	Baseline	Post	Change (95% CI)
Quadriceps strength, Nm	43.15 ± 2.57	69.73 ± 3.98	26.58 (25.55 to 27.60)	42.58 ± 3.11	55.95 ± 3.85	13.37 (12.46 to 14.29)
TUG, s	19.44 ± 1.71	12.70 ± 2.15	-6.74 (-7.09 to -6.39)	18.72 ± 1.57	15.64 ± 1.82	-3.08 (-3.28 to -2.88)
6MWT, m	281.77 ± 23.04	411.77 ± 26.46	130.00 (124.64 to 135.36)	281.40 ± 21.68	350.93 ± 23.49	69.53 (64.81 to 74.26)
Pain, NPRS	6.70 ± 0.79	2.20 ± 0.81	-4.50 (-4.92 to -4.08)	6.97 ± 0.89	4.10 ± 0.80	-2.87 (-3.38 to -2.35)

Outcome	Between-group difference in change, BFR – CP (95% CI)	Cohen's d	p-value
Quadriceps strength, Nm	13.20 (11.86 to 14.55)	5.06	< 0.001
TUG, s	-3.66 (-4.05 to -3.27)	4.84	< 0.001
6MWT, m	60.47 (53.47 to 67.46)	4.47	< 0.001
Pain, NPRS	-1.63 (-2.29 to -0.98)	1.29	< 0.001

Baseline and post-intervention values are mean ± SD. All within-group changes $p < 0.001$ (paired t-test). Between-group differences from independent t-tests on change scores; Cohen's d shown as absolute value. Results were unchanged with Wilcoxon signed-rank / Mann–Whitney U tests and with baseline-adjusted ANCOVA. For TUG and NPRS, negative values indicate improvement. BFR, blood flow restriction; CP, conventional physiotherapy; TUG, Timed Up and Go; 6MWT, Six-Minute Walk Test; NPRS, Numeric Pain Rating Scale.

Figure Legends

Figure 1. CONSORT flow diagram of participants through the trial. BFR, blood flow restriction.

Figure 2. Change from baseline to post-intervention in (A) isometric quadriceps strength, (B) Timed Up and Go time, (C) Six-Minute Walk Test distance and (D) pain on the Numeric Pain Rating Scale. Bars show mean change, error bars show SD and dots show individual participants. For (B) and (D), negative values indicate improvement. BFR + CP, blood flow restriction training plus conventional physiotherapy; CP, conventional physiotherapy.

Figure 1

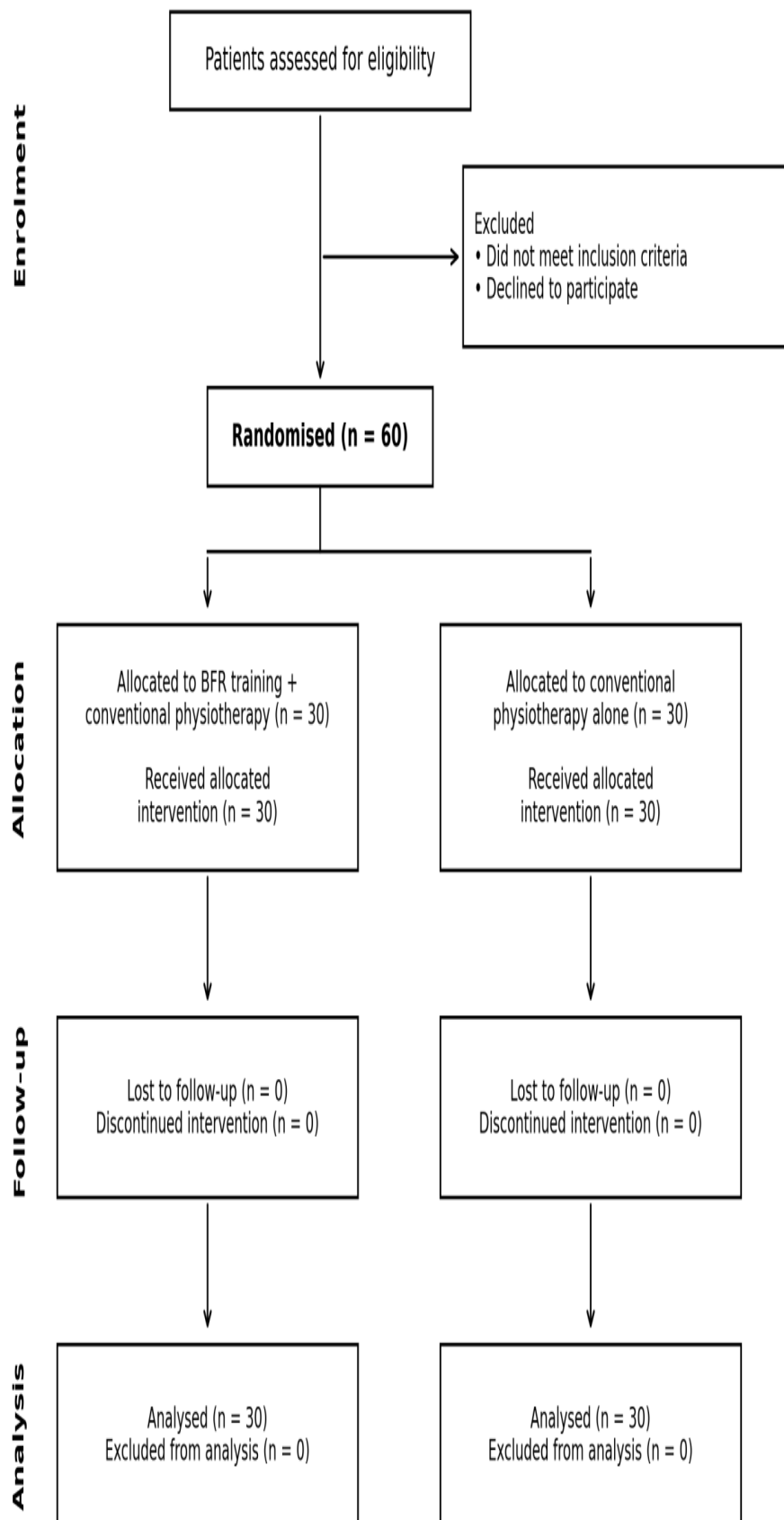
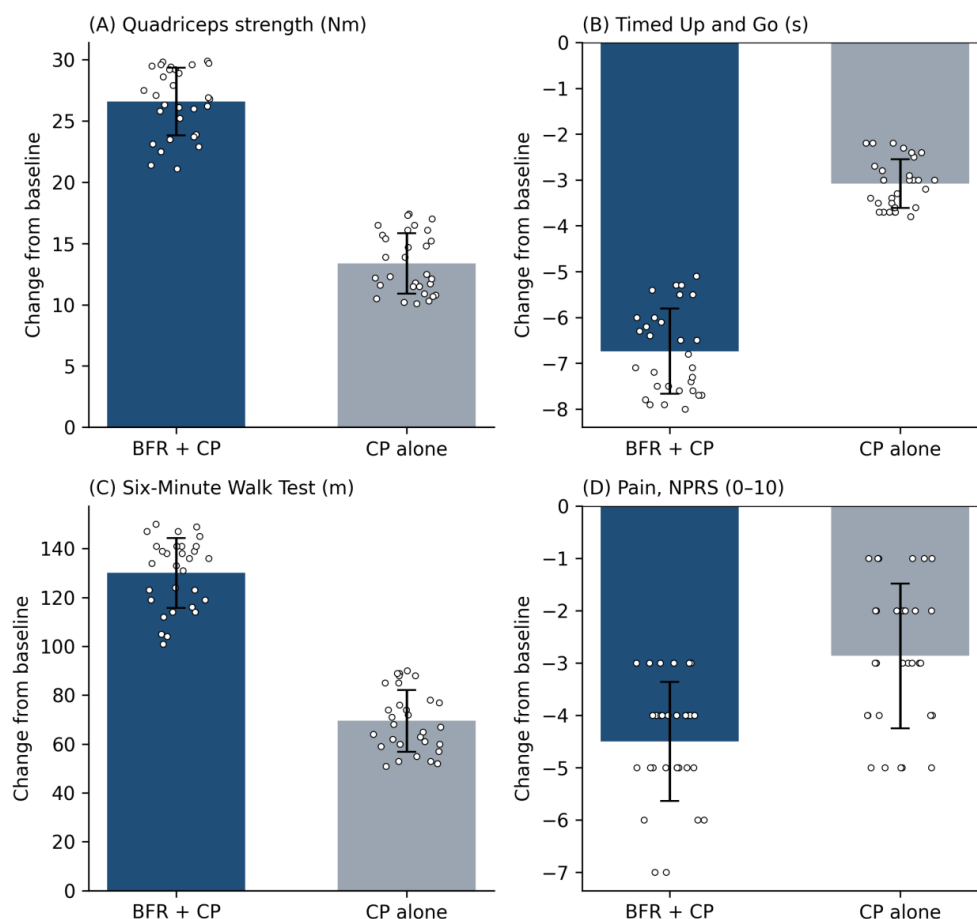


Figure 2



CONCLUSION

In patients recovering from primary unilateral TKR, adding low-load BFR training to conventional physiotherapy resulted in greater short-term improvements in quadriceps strength, functional mobility and walking endurance, and greater pain reduction, than conventional physiotherapy alone, with no adverse events in carefully screened patients. BFR training appears to be a feasible adjunct to early postoperative rehabilitation when high-load strengthening is not tolerated. Larger multicentre trials with longer follow-up are needed before firm recommendations can be made.

Declarations

Ethics approval and consent to participate: Approved by the Institutional Ethics Committee of the Institute of Applied Medicines and Research, Ghaziabad. Written informed consent was obtained from all participants.

Consent for publication: Not applicable.

Data availability: The de-identified dataset is available from the corresponding author on reasonable request.

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Conflicts of interest: The authors declare no conflicts of interest.

Author contributions: SJ: conceptualisation, data collection, intervention delivery, formal analysis, writing – original draft. VC: conceptualisation, methodology, supervision, writing – review and editing. Both authors approved the final manuscript.

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