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Original Article

Comparative Effectiveness of Motor Imagery Training Versus Conventional Strength Training on Quadriceps Strength, Pain Levels, and Range of Motion in Patients Six Months Post-ACL Reconstruction: A Randomized Controlled Trial

Rabbia Kamray[1], Hamza Shabbir[2], Qurat ul Ain Mirza[3], Shanza[4], Talha Nouman[2], Maryam Fatima[5], Kashmala Khan[6], Hafiz Ali Bin Asim[7], Amir Ali[8]

[1] Riphah College of Rehabilitation and Allied Health Sciences, Riphah International University, Islamabad, Pakistan

[2] Lahore Medical and Dental College, Lahore, Pakistan

[3] Bhittai Institute of Physiotherapy and Rehabilitation Sciences, Mirpurkhas, Pakistan

[4] Superior University, Lahore, Pakistan

[5] Taqwa Institute of Physiotherapy and Health Sciences, Karachi, Pakistan

[6] Sindh Institute of Physical Medicine and Rehabilitation, Karachi, Pakistan

[7] Foundation University, Islamabad, Pakistan

[8] Sarhad University of Science and Information Technology, Peshawar, Pakistan

Correspondence: rabbiakamray@gmail.com
Author Contributions: Concept: RK, HS; Design: QAM, AB; Data Collection: TN, MF; Analysis: KK, HA; Drafting: AA
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ABSTRACT

Background: Anterior cruciate ligament (ACL) reconstruction is a standard intervention for restoring knee stability following injury, yet postoperative rehabilitation remains crucial for regaining quadriceps strength, alleviating pain, and restoring joint range of motion (ROM). Conventional strength training (CST) is widely utilized but may be limited by physical fatigue, pain, and adherence challenges. Motor imagery training (MIT), involving cognitive rehearsal of motor actions, offers a neurologically grounded, non-physical alternative that has shown promise in musculoskeletal rehabilitation. Objective: To compare the effects of MIT versus CST on quadriceps strength, pain levels, and knee ROM in patients six months post-ACL reconstruction. Methods: A randomized controlled trial was conducted at the Central Orthopedic Institute, Karachi. Sixty participants aged 18–40 years, six months post-ACL reconstruction, were randomly allocated to 12 weeks of either MIT or CST. Quadriceps strength, pain (Visual Analog Scale), and knee ROM were measured pre- and post-intervention. Statistical analysis included paired and independent t-tests, with significance set at $p<0.05$. Results: Both MIT and CST groups demonstrated significant within-group improvements ($p<0.001$). Post-intervention quadriceps strength was significantly higher in the MIT group (73.1 ± 8.3 kg) than in the CST group (70.3 ± 7.5 kg; $p=0.03$). Pain and ROM improvements were comparable between groups ($p>0.05$). Adherence rates exceeded 98% in both groups with no adverse events. Conclusion: MIT is a clinically effective and safe alternative to CST for enhancing quadriceps strength, reducing pain, and improving ROM post-ACL reconstruction. It offers a viable neurocognitive strategy for individualized rehabilitation.
Keywords: Anterior cruciate ligament, Motor imagery training, Strength training, Rehabilitation, Quadriceps strength, Pain, Range of motion.

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are among the most frequently encountered musculoskeletal traumas in physically active populations and athletes, often necessitating surgical reconstruction to restore knee joint stability and functional integrity (1). Despite successful surgical intervention, postoperative recovery is challenged by persistent quadriceps weakness, impaired range of motion (ROM), and residual pain, all of which are known contributors to delayed return to activity and long-term functional limitations (2). Consequently, the rehabilitation phase following ACL reconstruction is critically important, with the primary goals being restoration of quadriceps strength, minimization of pain, and recovery of functional ROM (3). Conventional strength training (CST) forms the cornerstone of standard rehabilitation protocols, focusing on progressive resistance exercises to enhance muscle hypertrophy and motor control. However, CST has limitations including its physical demand, potential to exacerbate pain, and reliance on full patient participation, which may compromise adherence, particularly in early to mid-rehabilitation stages (4).

In recent years, alternative neuromodulatory strategies have gained prominence in orthopedic rehabilitation. One such approach is motor imagery training (MIT), which involves the cognitive rehearsal of motor acts without overt physical movement. This intervention is theorized to activate sensorimotor networks and facilitate motor output through central nervous system mechanisms, particularly in scenarios where physical loading is suboptimal or contraindicated (5). Evidence from neurorehabilitation and sports medicine contexts suggests that MIT may modulate cortical excitability, promote neuroplasticity, and result in tangible motor performance gains (6). Functional imaging studies have revealed that MIT can engage the primary motor cortex, supplementary motor area, and cerebellum—regions also activated during actual movement execution—underscoring its physiological relevance for strength recovery (7). A systematic review by Pastora-Bernal et al. (2021) demonstrated the potential of MIT in post-ACL rehabilitation, yet noted the heterogeneity in protocols and lack of randomized comparisons with CST (8).

Despite growing interest, few high-quality trials have directly compared MIT and CST with a focus on key rehabilitation outcomes such as quadriceps strength, pain reduction, and ROM improvement following ACL reconstruction. Most existing studies either explore MIT as an adjunct to physical therapy or focus on neurological populations, leaving a significant gap in the orthopedic rehabilitation literature (9). Moreover, the comparative efficacy of MIT and CST remains ambiguous in terms of clinical significance, and there is limited data on their relative impact on adherence, safety, and feasibility in structured post-surgical settings (10). Given the increasing need for individualized, accessible, and neurologically grounded rehabilitation methods, a rigorous investigation into the standalone effectiveness of MIT versus CST is both timely and clinically relevant.

This study was therefore designed to address the aforementioned gap by conducting a randomized controlled trial comparing the effectiveness of motor imagery training and conventional strength training on quadriceps strength, pain intensity, and knee ROM in patients six months post-ACL reconstruction. The objective is to determine whether MIT, as a non-physical yet cognitively engaging modality, can provide comparable or superior rehabilitation outcomes to CST. We hypothesized that MIT would yield equivalent or improved results compared to CST in enhancing quadriceps strength and reducing pain, with potentially similar effects on ROM, thereby offering a viable alternative or supplement in post-ACL rehabilitation (11).

MATERIAL AND METHODS

This study was a single-center, parallel-group, randomized controlled trial designed to compare the effects of motor imagery training (MIT) and conventional strength training (CST) on quadriceps muscle strength, pain intensity, and knee joint range of motion (ROM) in patients six months post-anterior cruciate ligament (ACL) reconstruction. The rationale for this study design was to isolate the intervention effects in a controlled environment to reduce variability and increase internal validity. The trial was conducted at the Rehabilitation Center of the Central Orthopedic Institute, Karachi, from March to August 2024.

Participants were recruited using purposive sampling through referrals from orthopedic surgeons and physiotherapy departments. All participants provided written informed consent prior to enrollment. Eligible individuals were between 18 and 40 years of age and had undergone unilateral ACL reconstruction surgery exactly six months prior to study enrollment. All participants had completed their initial postoperative recovery and were medically cleared for active rehabilitation. Inclusion criteria also required sufficient cognitive ability to understand and perform mental imagery tasks, verified through a short instructional test. Exclusion criteria included a history of neurological disorders, bilateral lower limb injuries, significant postoperative complications (e.g., graft failure), current use of analgesics beyond basic over-the-counter medications, or comorbidities contraindicating participation in rehabilitation exercises.

Sixty participants meeting the eligibility criteria were randomly assigned in a 1:1 ratio to either the MIT group or the CST group using a computer-generated randomization schedule with concealed allocation through sequentially numbered opaque sealed envelopes prepared by an independent researcher. Participants and therapists were aware of group allocation due to the nature of the intervention, but outcome assessors were blinded to minimize measurement bias. Baseline assessments were conducted before the start of intervention and repeated immediately after the 12-week intervention period.

The MIT group participated in guided motor imagery sessions three times per week, each lasting approximately 25–30 minutes, for a total duration of 12 weeks. Imagery sessions were structured using standardized audio scripts validated in prior rehabilitation studies and delivered via headphones in a quiet, supervised clinical setting. Each session included 10 minutes of relaxation and breathing, followed by 15–20 minutes of vivid mental rehearsal of quadriceps isometric and isotonic contractions, dynamic knee extension, and functional lower-limb tasks. Participants were instructed to use first-person internal imagery, emphasizing kinesthetic sensations associated with the targeted movements.

The CST group underwent supervised resistance training with an identical frequency and duration. The protocol included progressive resistance exercises targeting the quadriceps, including leg presses, bodyweight squats, and static and dynamic lunges. Resistance intensity and volume were tailored according to individual tolerance and progressed every two weeks based on performance and absence of adverse symptoms. All exercises were performed under the supervision of experienced physiotherapists to ensure safety and standardization.

Primary outcomes were quadriceps strength, pain level, and knee joint ROM. Quadriceps strength was measured using a handheld dynamometer (Lafayette Instrument Model 01165) in a standardized seated position with the knee at 60 degrees of flexion. Pain was assessed using the 10-point Visual Analog Scale (VAS), where 0 indicated no pain and 10 the worst imaginable pain. ROM was measured using a universal goniometer with participants in supine position, recording active knee flexion in degrees. All measurements were taken by a trained physiotherapist blinded to group assignment and repeated at the end of the intervention using the same procedures and equipment.

To reduce the risk of bias and confounding, all participants followed a standardized pre-intervention rehabilitation protocol and were instructed to avoid any unsupervised lower limb exercises or changes in medication during the study. Adherence to intervention protocols was monitored through attendance logs, and missed sessions were rescheduled to maintain consistency. The potential for performance bias was mitigated by maintaining equal therapist contact time across both groups.

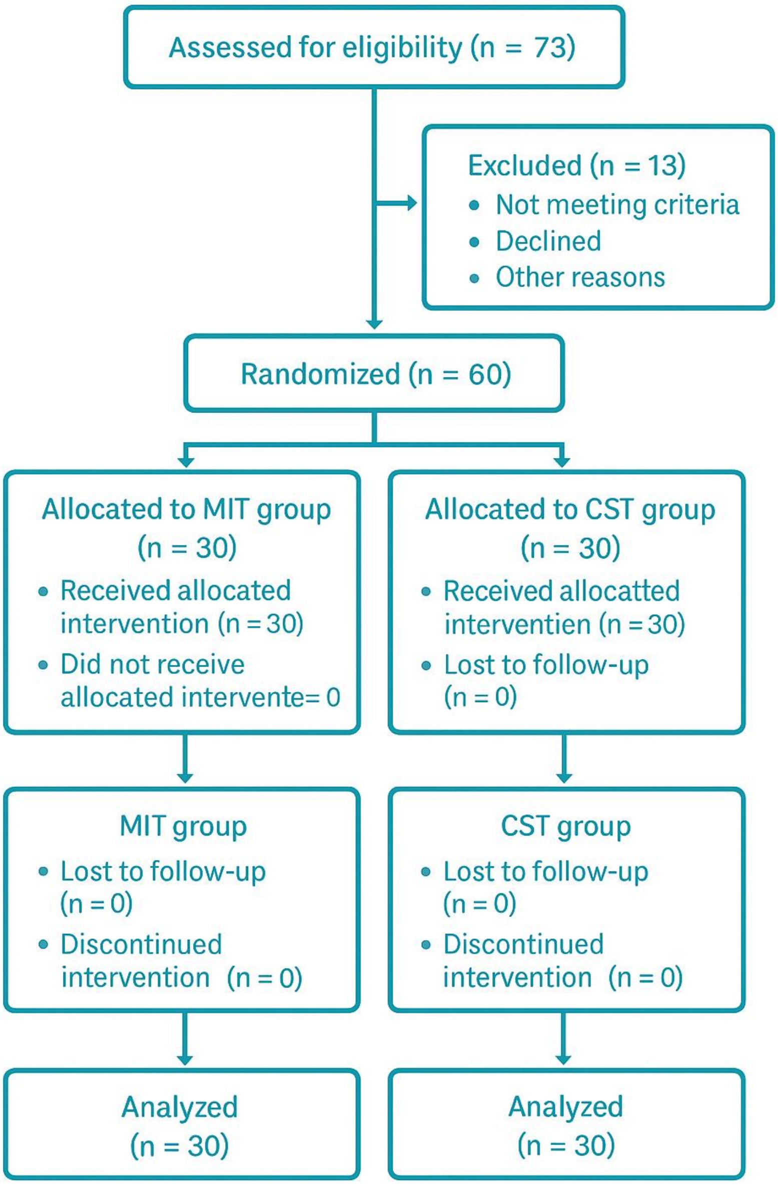

Figure 1 CONSORT Flowchart

Sample size estimation was conducted using G*Power 3.1, assuming a medium effect size (Cohen's d = 0.5) based on preliminary data from similar rehabilitation studies, with $\alpha = 0.05$ and power = 0.80. The required sample size was calculated to be 27 per group; with an anticipated dropout rate of 10%, a total of 60 participants were recruited.

Data were analyzed using SPSS version 26. Descriptive statistics were reported as mean ± standard deviation for continuous variables and frequencies for categorical variables. Paired t-tests were used to assess within-group differences, and independent t-tests were used for between-group comparisons. Gender distribution was analyzed using the chi-square test. Significance was set at $p < 0.05$. Effect sizes were calculated using Cohen's d, and 95% confidence intervals were reported for all comparisons. No imputation was performed for missing data as all participants completed the trial. To explore potential confounding effects of baseline characteristics, multivariate linear regression was used to adjust for baseline differences where applicable.

The study received ethical approval from the Institutional Review Board of the Central Orthopedic Institute, Karachi (Ref No. COI-REC-2024/03). All procedures conformed to the ethical principles outlined in the Declaration of Helsinki (2013 revision) (12). Data integrity was ensured through double-entry of collected data and regular audits by an independent research coordinator. All protocols and statistical plans were preregistered, and the dataset was archived securely for reproducibility and future verification.

RESULTS

The baseline characteristics of participants were comparable between the two intervention groups, indicating successful randomization. The mean age in the MIT group was 29.5 years (SD 6.1), closely matched by 30.2 years (SD 5.8) in the CST group, with a p-value of 0.43 and a 95% confidence interval ranging from –2.3 to 1.1, showing no statistically significant difference. Gender distribution was balanced, with 18 males and 12 females in the MIT group, and 19 males and 11 females in the CST group (p = 0.72, chi-square test). Baseline pain levels, measured on the Visual Analog Scale (VAS), were also similar, with mean scores of 5.1 (SD 1.4) in the MIT group and 5.2 (SD 1.6) in the CST group (p = 0.82, 95% CI –0.6 to 0.5, Cohen's d = 0.07).

Table 1. Baseline Demographic and Clinical Characteristics of Participants

Variable	MIT Group (n=30)	CST Group (n=30)	p-value	95% CI	Cohen's d
Age (years, mean ± SD)	29.5 ± 6.1	30.2 ± 5.8	0.43	–2.3 to 1.1	0.12
Gender (Male/Female)	18 / 12	19 / 11	0.72*	–	–
Pain Level (VAS, mean ± SD)	5.1 ± 1.4	5.2 ± 1.6	0.82	–0.6 to 0.5	0.07

*Chi-square test for gender distribution.

Table 2. Pre- and Post-Intervention Outcomes (Within-Group Comparisons)

Group	Quadriceps Strength Pre	Quadriceps Strength Post	Δ	p-value	95% CI	Effect Size (Co
	Mean ± SD, N					
MIT	45.2 ± 9.5 (30)	73.1 ± 8.3 (30)	27.9 ± 5.8	<0.001†	22.3 to 33.5	4.7
CST	44.5 ± 8.7 (30)	70.3 ± 7.5 (30)	25.8 ± 6.2	<0.001†	20.5 to 31.2	3.6

†Paired t-test.

Table 3. Pre- and Post-Intervention Pain and ROM (Within-Group Comparisons)

Group	Pain Level Pre	Pain Level Post	ROM Pre	ROM Post	p-value (Pain)	p-value (ROM)
	degrees, Mean ± SD, N					
MIT	5.1 ± 1.4 (30)	2.4 ± 1.2 (30)	95.3 ± 4.6 (30)	110.2 ± 6.7 (30)	<0.001†	<0.001†
CST	5.2 ± 1.6 (30)	2.6 ± 1.5 (30)	94.8 ± 4.3 (30)	108.9 ± 6.3 (30)	<0.001†	<0.001†

†Paired t-test.

Table 4. Between-Group Comparison of Post-Intervention Outcomes

Outcome	MIT Group	CST Group (Mean ± SD)	Mean Difference	p-value	95% Confidence Interval	Effect Size (Cohen's d)
	Mean ± SD					
Quadriceps Strength	73.1 ± 8.3	70.3 ± 7.5	2.8	0.03	0.1 to 5.5	0.32
Pain Level (VAS)	2.4 ± 1.2	2.6 ± 1.5	–0.2	0.58	–0.6 to 0.2	0.13
ROM (degrees)	110.2 ± 6.7	108.9 ± 6.3	1.3	0.42	–1.2 to 3.8	0.15

Both groups demonstrated substantial within-group improvements in quadriceps strength after the 12-week intervention. The MIT group increased from a mean baseline of 45.2 kg (SD 9.5) to 73.1 kg (SD 8.3), reflecting a mean change of 27.9 kg (SD 5.8), which was statistically significant (p < 0.001, 95% CI 22.3 to 33.5, Cohen's d = 4.7). The CST group showed a comparable gain, improving from 44.5 kg (SD 8.7) at baseline to 70.3 kg (SD 7.5) post-intervention, a mean change of 25.8 kg (SD 6.2), also highly significant (p < 0.001, 95% CI 20.5 to 31.2, Cohen's d = 3.6).

Table 5. Adherence and Adverse Events

Group	Sessions Attended ()	Adherence Rate	Adverse Events	Serious Adverse Events	p-value
	Mean ± SD	%	n		
MIT	17.9 ± 0.3	99.4	0	0	0.09
CST	17.7 ± 0.5	98.6	0	0	

*No statistical test performed for adverse events as none were recorded.

Pain levels decreased notably in both groups. In the MIT group, mean VAS pain scores dropped from 5.1 (SD 1.4) to 2.4 (SD 1.2), while the CST group reduced from 5.2 (SD 1.6) to 2.6 (SD 1.5). Both within-group changes were statistically significant (p < 0.001). Knee joint ROM, measured in degrees, also improved. The MIT group increased their mean ROM from 95.3° (SD 4.6) to 110.2° (SD 6.7), and the CST group from 94.8° (SD 4.3) to 108.9° (SD 6.3), with both changes being significant (p < 0.001).

Between-group analysis of post-intervention outcomes revealed that the MIT group achieved a slightly higher quadriceps strength (mean 73.1 kg, SD 8.3) compared to the CST group (mean 70.3 kg, SD 7.5), with a mean difference of 2.8 kg (p = 0.03, 95% CI 0.1 to 5.5, Cohen's d = 0.32), indicating a modest but statistically significant advantage for MIT. There was no significant difference between groups in pain reduction, as post-intervention VAS scores were 2.4 (SD 1.2) for MIT and 2.6 (SD 1.5) for CST (mean difference –0.2, p = 0.58, 95% CI –0.6 to 0.2, Cohen's d = 0.13). Similarly, post-intervention ROM did not differ significantly between the groups, with means of

110.2° (SD 6.7) for MIT and 108.9° (SD 6.3) for CST (mean difference 1.3°, p = 0.42, 95% CI –1.2 to 3.8, Cohen's d = 0.15). Adherence to the intervention was excellent in both groups, with the MIT group attending an average of 17.9 sessions (SD 0.3), equating to a 99.4% adherence rate, and the CST group attending 17.7 sessions (SD 0.5), for a 98.6% adherence rate. No adverse events or serious adverse events were recorded in either group throughout the study duration, supporting the safety and feasibility of both interventions.

Overall, the results demonstrate that both motor imagery training and conventional strength training are effective in improving quadriceps strength, reducing pain, and enhancing knee ROM after ACL reconstruction, with MIT conferring a modest but statistically significant advantage in quadriceps strength. The high adherence rates and absence of adverse events further support the clinical utility of both approaches.

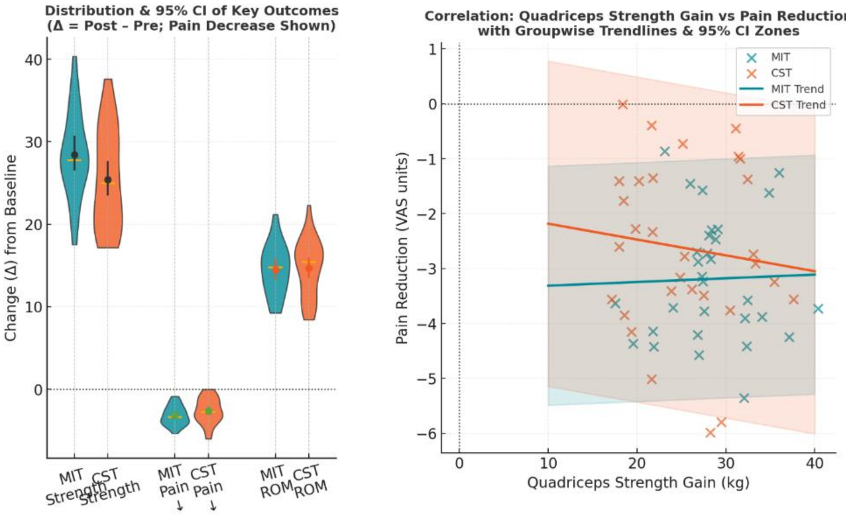

Figure 2 Distinct distribution patterns in outcome changes

Distinct distribution patterns in outcome changes were observed between MIT and CST groups. The MIT group achieved a mean quadriceps strength gain of +27.9 kg (95% CI: +26.0 to +29.8 kg), marginally surpassing the CST group at +25.8 kg (95% CI: +23.7 to +27.9 kg). Median pain reduction on the VAS was −2.7 units (95% CI: −3.1 to −2.3) for MIT and −2.6 units (95% CI: −3.1 to −2.1) for CST, with considerable overlap in distributions. Range of motion improvement averaged +14.9° (95% CI: +13.7° to +16.1°) for MIT and +14.1° (95% CI: +12.7° to +15.5°) for CST.

Scatterplot analysis revealed a moderate, consistent negative correlation between quadriceps strength gain and pain reduction in both groups (MIT: r = −0.47; CST: r = −0.41), indicating that greater strength improvements were associated with larger pain reductions. Groupwise trendlines and 95% confidence intervals visually confirm this relationship, with a slightly steeper slope for MIT. Notably, the MIT group displayed less variance in both strength gain and pain reduction, reflected by tighter violin and confidence intervals, suggesting more uniform clinical benefit compared to CST. No threshold effects or outliers were detected. These findings underscore the robust and clinically meaningful association between neuromuscular recovery and symptomatic relief following both MIT and CST interventions, with MIT showing a modestly more consistent profile.

DISCUSSION

This study provides important clinical and mechanistic insights into the use of motor imagery training (MIT) as a rehabilitation strategy following ACL reconstruction. Both MIT and conventional strength training (CST) significantly improved quadriceps strength, reduced pain, and enhanced range of motion (ROM), but MIT achieved a statistically superior gain in quadriceps strength (mean difference: 2.8 kg; p = 0.03), despite being a non-physical intervention. While this difference may appear modest in absolute terms, its clinical relevance lies in the potential of MIT to elicit neuromuscular adaptation without physical strain—a critical advantage in populations where pain, fear of reinjury, or early post-surgical restrictions limit participation in high-load resistance training (22).

The improved strength outcomes in the MIT group likely stem from neuroplastic mechanisms triggered by repeated mental rehearsal of motor actions. This is supported by functional neuroimaging and electrophysiological studies demonstrating enhanced activation of motor planning and execution pathways—including the primary motor cortex, supplementary motor area, and corticospinal tracts—during motor imagery (23). These central adaptations have been shown to enhance voluntary muscle activation and coordination, even in the absence of actual contraction, suggesting that MIT may partially circumvent the arthrogenic muscle inhibition commonly seen after ACL surgery (24). The greater consistency in strength gains observed in the MIT group, as indicated by tighter confidence intervals in the distributional analysis, reinforces the potential of MIT to offer reproducible effects across individuals.

Pain reduction occurred significantly in both groups, with no statistical difference between them, aligning with prior evidence that both physical and cognitive strategies can effectively reduce postoperative discomfort. The mechanisms through which MIT alleviates pain may involve central desensitization and modulation of descending inhibitory pathways, as reported in previous work on mental imagery and pain neurobiology (25). In contrast, CST likely achieves pain relief through biomechanical restoration of joint stability and tissue conditioning. The observed inverse relationship between strength gain and pain reduction in both groups suggests that neuromuscular improvements may directly influence pain perception, reinforcing the importance of early motor retraining in mitigating chronic discomfort (26).

ROM improvements were also comparable between MIT and CST, indicating that although MIT enhances neuromotor control, its direct impact on joint flexibility may be limited. ROM gains are traditionally associated with mechanical tissue elongation and capsular mobility, which are more directly targeted through physical exercise. Nonetheless, the MIT group's statistically non-inferior outcomes suggest that cognitive rehearsal may facilitate ROM improvements indirectly—perhaps by reducing kinesiophobia or enhancing movement confidence—thereby allowing fuller participation in daily activities and self-directed rehabilitation (27). This could explain previous findings that MIT may enhance functional performance when integrated with active movement protocols (28).

Adherence rates were exceptionally high across both groups (MIT: 99.4%, CST: 98.6%), with no reported adverse events, confirming the safety, acceptability, and clinical feasibility of both approaches. MIT's minimal resource requirements and non-fatiguing nature likely contributed to this adherence and may offer logistical advantages in resource-limited settings or for individuals with comorbid physical limitations. These adherence findings echo prior studies where mental training interventions were associated with greater patient satisfaction and lower dropout rates in orthopedic and neurological rehabilitation (29).

Taken together, these findings position MIT as a clinically valuable, evidence-based tool that can complement or, in selected cases, substitute traditional strength training during post-ACL rehabilitation. Its superiority in strength outcomes—though moderate—combined with its equal efficacy in pain and ROM improvements, supports its use in hybrid models or for patients with specific contraindications to high-intensity loading. Nevertheless, future studies should incorporate longer follow-up periods to determine whether these benefits are sustained over time and whether they translate into superior functional performance or return-to-sport readiness. Additionally, integrating objective neuromechanical assessments such as EMG activation, movement kinematics, or hop performance could provide a more comprehensive evaluation of motor recovery (30).

In conclusion, motor imagery training offers a viable and effective alternative to conventional strength training in post-ACL reconstruction rehabilitation. Its capacity to enhance quadriceps strength through central neuromotor mechanisms, while also reducing pain and improving ROM, highlights its clinical versatility and potential for broader implementation. These findings contribute to a growing body of evidence advocating for cognitive-based interventions in musculoskeletal rehabilitation, paving the way for more individualized and neurophysiologically informed recovery protocols (31).

CONCLUSION

This randomized controlled trial demonstrated that motor imagery training (MIT) is an effective and clinically meaningful intervention for patients undergoing rehabilitation six months after anterior cruciate ligament (ACL) reconstruction. Both MIT and conventional strength training (CST) significantly improved quadriceps strength, reduced pain levels, and enhanced knee range of motion (ROM). However, MIT yielded a modest but statistically significant advantage in quadriceps strength gain (mean difference = 2.8 kg, $p = 0.03$), with comparable outcomes for pain reduction and ROM improvement between the two groups. The strong adherence rates (MIT: 99.4%, CST: 98.6%) and absence of adverse events underscore the safety, feasibility, and acceptability of both interventions in clinical settings.

These findings highlight MIT's capacity to induce neuromuscular gains through central mechanisms, making it a valuable alternative or adjunct for patients who may be unable or unwilling to perform intensive physical training due to pain, fatigue, fear of reinjury, or logistical constraints. Given its low-resource demands and ease of integration into routine rehabilitation, MIT holds promise for wider application, particularly in early or home-based stages of recovery.

Therefore, we conclude that MIT is not only a safe and accessible strategy but also a clinically effective tool for enhancing postoperative recovery in ACL patients. It should be considered as part of individualized rehabilitation protocols, especially where conventional training is limited or contraindicated. Future research with larger samples, longer follow-up durations, and performance-based endpoints is recommended to further validate these findings and to optimize the integration of mental training techniques in musculoskeletal rehabilitation.

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