Original Article

Effects of Functional Rehabilitation on Muscle Strength, Dynamic Balance and Functional Performance 1 Year after Anterior Cruciate Ligament Reconstruction: A Randomised Controlled Trial

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Abstract

Background: Return to sport (RTS) success rates remain suboptimal for high sports demand individuals (HSDs) following anterior cruciate ligament reconstruction (ACLR). Traditional rehabilitation model (TRM) primarily focuses on strength recovery and range of motion but demonstrates deficiencies in neuromuscular control and sport-specific conditioning. **Aims:** This study aimed to compare the effects of functional rehabilitation model (FRM) versus Traditional rehabilitation model (TRM) on post-operative functional recovery and RTS outcomes in HSDs. **Methods:** A prospective single-blind randomised controlled trial was conducted including 64 HSDs who underwent ACLR (exercise ≥3 times per week, Tegner score >5), randomly allocated to the FRM group (n = 32) and TRM group (n = 32). The FRM group received a performance-based progressive 24-week rehabilitation protocol incorporating multimodal sensory training, closed-chain exercises, unstable surface proprioceptive training and sport-specific skill integration. The TRM group received a standard time-oriented 24-week rehabilitation protocol. The primary outcomes included 48-week RTS rate and functional recovery trajectory. The secondary outcomes included isokinetic strength, single-leg hop tests, modified star excursion balance test, proprioception and patient-reported outcomes (International Knee Documentation Committee [IKDC], Lysholm and Anterior Cruciate Ligament-Return to Sport after Injury [ACL-RSI]). Assessment time points included pre-operative baseline, 24 weeks and 48 weeks postoperatively. Repeated measures analysis of variance was used to evaluate longitudinal changes. **Results:** Fifty-seven patients completed follow-up (retention rate: 89.1%). The FRM group demonstrated significantly higher 48-week successful RTS rate compared to the TRM group (89.3% vs. 62.1%, P = 0.038), with relative risk 1.44 (95% confidence interval: 1.05–1.97) and number needed to treat 3.7. Repeated measures analysis revealed that the FRM group significantly outperformed the TRM group in quadriceps peak torque (48 weeks: 124.17 ± 7.25 vs. 98.42 ± 8.73 Nm, P < 0.001) and limb symmetry index (89.15% ± 3.85% vs. 69.45% ± 5.15%, P < 0.001). In single-leg hop tests, the FRM group demonstrated superior performance in lateral hop time (5.54 ± 2.25 vs. 7.84 ± 3.37 s, P = 0.004) and box hop symmetry index (97.50% ± 29.60% vs. 76.20% ± 31.40%, P = 0.011). Proprioceptive testing showed that the FRM group had smaller position sense errors at 30° (2.83° ± 1.63° vs. 4.25° ± 1.85°, P = 0.002) and 45° knee flexion angles (6.37° ± 1.69° vs. 7.57° ± 1.73°, P = 0.008). Patient-reported outcomes demonstrated the FRM group superiority in IKDC (89.45 ± 9.72 vs. 83.45 ± 12.73, P = 0.028), Lysholm (88.71 ± 5.78 vs. 76.12 ± 12.38, P < 0.001) and ACL-RSI scores (79.52 ± 8.17 vs. 70.35 ± 10.24, P < 0.001). The FRM group exhibited sustained linear improvement patterns, while the TRM group showed a recovery plateau after 24 weeks. **Conclusion:** Compared to TRM, FRM significantly improved functional recovery trajectories and RTS outcomes in HSDs through enhanced neuromuscular control, improved dynamic performance and increased psychological readiness.

Keywords: Anterior cruciate ligament reconstruction, functional rehabilitation, high sports demand individuals, neuromuscular training, return to sport

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Introduction

Anterior cruciate ligament (ACL) injuries represent one of the most challenging clinical problems in sports medicine, not only due to their high incidence in high-intensity sports but also because of their profound impact on athletes' careers. In the United States, this injury occurs in approximately 1 in every 3500 individuals annually,[1] with an increasing trend among adolescents.[2] These data underscore the urgent need for establishing effective rehabilitation strategies.

The complexity of ACL injuries extends far beyond simple structural disruption. The ACL's rich mechanoreceptor network plays a crucial role in maintaining knee joint proprioception and neuromuscular control.[3] Functional loss of these receptors leads to decreased proprioceptive input and secondary neuromuscular adaptive changes, including quadriceps inhibition, delayed Hamstring (HS) activation and altered movement patterns.[4]

High sports demand individuals (HSDs), defined as individuals actively participating in sports more than three times per week with Tegner scores greater than 5, face particularly complex challenges.[5] Successful return to competitive sports requires not only structural integrity and strength recovery but also complex sensorimotor integration, rapid reaction capabilities, psychological resilience and sport-specific skills.[6]

However, current return to sport (RTS) outcomes remain concerning. Despite advances in surgical techniques, RTS success rates remain at 40%–50%,[7] with reinjury rates reaching 15%–20% within 2 years.[8] This suggests fundamental deficiencies in the traditional 'repair-strengthen-return' rehabilitation model.

Traditional rehabilitation model (TRM) emphasises progressive rehabilitation according to tissue healing timelines, including pain control, range of motion restoration, isolated strength training and basic balance exercises. While effective in restoring basic function, TRM exhibits critical deficiencies: excessive reliance on time-oriented rather than function-oriented criteria, lack of specific neuromuscular control training, insufficient sport-specificity and marginalised psychological factors.[9]

The emerging functional rehabilitation model (FRM) is based on neuromuscular control theory, motor learning principles and the biopsychosocial model.[10] Core characteristics include function-based progression criteria, early proprioceptive and neuromuscular training, multi-planar movement patterns, unstable surface training, sport-specific skill integration and systematic psychological assessment. Neuroscience research demonstrates that FRM promotes cortical remodelling and corticospinal pathway reorganisation.[11,12] Motor learning principles guide progressive skill acquisition,[13] while psychological factors significantly influence RTS success.[14]

Despite increasingly sophisticated theoretical foundations, high-quality randomised controlled trials comparing FRM and TRM in high sports demand populations remain scarce. Most studies suffer from limitations including insufficient sample sizes, short follow-up periods and lack of standardised protocols.

Based on these clinical needs, this study designed a rigorous prospective randomised controlled trial to systematically compare FRM versus TRM effects on post-operative functional recovery and RTS outcomes in HSDs. The study's innovation includes: (1) standardised intervention protocols specifically targeting HSDs; (2) 48-week long-term follow-up; (3) comprehensive multidimensional assessment; and (4) in-depth exploration of neuromuscular mechanisms.

Methods

Study design and setting

This prospective, single-blind, randomised controlled trial was conducted at the Affiliated Hospital of Xi'an Medical University between April 2024 and May 2025. The study followed the Declaration of Helsinki ethical guidelines and adhered to the Consolidated Standards of Reporting Trials guidelines.[15] All participants received a comprehensive verbal explanation of the study procedures and completed a written informed consent form prior to enrolment.

The study protocol was approved by the Medical Ethics Review Committee of Xi'an Medical University (approval number: XYLS2024127). All participants provided written informed consent to participate in the study. The trial was prospectively registered with the Chinese Clinical Trial Registry under registration number ChiCTR2500104413 on June 17, 2025 (http://www.chictr.org.cn/).

An independent Data Safety Monitoring Board was established to provide the oversight of research implementation and ensure data quality control throughout the study duration. All study procedures were conducted in accordance with Good Clinical Practice guidelines and institutional protocols.

Participants

Patients with post-operative ACL injuries were recruited from June 2024 to September 2024 in the outpatient clinic of the First Affiliated Hospital of Xi'an Medical University and met the inclusion criteria.

Inclusion criteria of this study were as follows: (1) HSDs aged 18–45 years, defined as actively participating in sports activities more than three times per week, Tegner score greater than 5, and engaging in level I sports involving cutting and pivoting activities before injury; (2) primary ACL reconstruction (ACLR) surgery using autologous bone-patellar tendon-bone or HS grafts; (3) unilateral complete ACL rupture confirmed by magnetic resonance imaging; (4) initiation of physical therapy within 8 weeks postoperatively; (5) no cognitive impairment, able to understand and comply with rehabilitation training and follow-up requirements; and (6) signed informed consent with commitment to complete 48-week follow-up.

Exclusion criteria of this study were as follows: (1) ACL revision surgery or previous ipsilateral knee surgery history; (2) other Grade C or D ligament injuries according to International Knee Documentation Committee (IKDC) classification; (3) concurrent meniscal repair surgery; (4) Grade III or IV cartilage damage according to the International Cartilage Regeneration & Joint Preservation Society (ICRS) classification; (5) musculoskeletal, neurological or vestibular system diseases affecting lower extremity function; (6) chronic or systemic diseases potentially causing peripheral neuropathy or proprioceptive deficits (such as diabetes and chronic renal failure); (7) cognitive, psychiatric or psychological problems affecting rehabilitation compliance; (8) balance dysfunction or medication use potentially affecting balance; and (9) pregnant or lactating women.

Withdrawal criteria of this study were as follows: (1) severe complications such as infection and deep vein thrombosis of the lower limbs during the experiment; (2) those who cannot maintain the experimental plan or choose other treatment methods, which affects the recovery effect; (3) poor compliance; and (4) fall off on their own due to various reasons, etc.

Sample size calculation and randomisation

The sample size calculation was based on the primary outcome of RTS rate. According to literature reports, the RTS rate for traditional rehabilitation methods is approximately 50%,[16] and the FRM was expected to increase the RTS rate to 80%. Sample size calculation was performed using G*Power 3.1 software (Heinrich Heine University, Düsseldorf, Germany) with repeated measures analysis of variance, medium effect size ($f = 0.25$), $\alpha = 0.05$ (two-sided test), $\beta = 0.20$ (80% power) and 1:1 allocation ratio, yielding 22 participants per group. Considering a potential 30% dropout rate, the final sample size was determined as 32 participants per group, totalling 64 participants.

Randomisation was implemented using computer-generated random number tables by research personnel not involved in recruitment or treatment. The random sequence used block randomisation methods. Random allocation results were sealed in opaque envelopes and numbered sequentially. Participants meeting the inclusion criteria were randomly allocated by the research coordinator opening envelopes sequentially after completing baseline assessment.

Blinding design

Due to the nature of rehabilitation interventions, blinding of therapists and participants was not feasible. To minimise bias, the following measures were implemented: (1) participants remained blinded to group allocation and control group intervention details, knowing only their assigned treatment protocol; (2) outcome assessors were completely blinded to group allocation, with assessments conducted in independent examination rooms; (3) data entry and statistical analysis personnel remained blinded to group allocation; and (4) standardised assessment procedures and assessor training were established to ensure assessment quality and consistency.

Intervention protocols

- TRM group: A standard 24-week rehabilitation protocol based on tissue healing timelines was implemented, strictly following internationally accepted ACL post-operative rehabilitation guidelines[17]
- FRM group: A performance-based progressive 24-week rehabilitation protocol was implemented, with phase transitions based on functional performance rather than fixed time intervals.

Key characteristics of FRM included closed-chain exercise-dominant strength training, neuromuscular electrical stimulation combined with active contractions, multi-directional unstable surface proprioceptive training, progressive functional movement patterns, sport-specific skill integration and psychological readiness assessment and intervention.[18-20]

Outcome measures

All assessments were conducted by specially trained assessors in standardised environments, with assessors remaining blinded to group allocation. Assessment time points included pre-operative baseline, 24 weeks postoperatively (intervention completion) and 48 weeks postoperatively (long-term follow-up).

Primary outcomes

- 48-week RTS rate: Defined using multidimensional criteria requiring simultaneous satisfaction of the following conditions: (1) passing ≥2 functional tests (such as single-leg hop tests and balance tests); (2) adequate psychological readiness (ACL-Return to Sport after Injury [RSI] score ≥70); (3) quadriceps and HS strength symmetry ≥90%; (4) post-operative time ≥8 months; and (5) patient self-report of returning to pre-injury sport level with continuous participation ≥4 weeks
- Functional recovery trajectory: Assessment of longitudinal change patterns from 24 to 48 weeks through repeated measures analysis, focusing on recovery rate, plateau phenomena and between-group differences.

Secondary outcomes

Isokinetic strength testing

Standardised testing was performed using the Biodex Multi-Joint Isokinetic Testing System (Biodex Medical System, New York, USA). Participants underwent 5-min warm-up on a power bicycle before testing. Standard seated position was used with seat adjustment according to participant height, 90° backrest angle and dynamometer axis aligned with knee joint axis. Testing was conducted at 60°/s (slow-speed strength testing, 1 set of 5 repetitions) and 180°/s (fast-speed strength testing, 1 set of 10 repetitions) angular velocities for quadriceps and HSs. Testing parameters included peak torque (PT), body weight (BW), total work (TW), limb symmetry index (LSI) and Hamstring to quadriceps ratio (H/Q).

Single-leg hop tests

Three standardised test items were included – (1) single-leg hop for distance: take-off and landing on the same leg, measuring maximum distance with stable landing maintained for 2 s, best of 3 trials recorded; (2) single-leg lateral hop: complete 10 lateral single-leg hops between two lines spaced 30 cm apart, recording time; (3) single-leg box hop: complete 10 single-leg hops up and down on a 20-cm high jump box, recording time. Affected limb absolute values and LSI (affected/unaffected × 100%) were calculated.

Modified star excursion balance test

A standardised testing protocol was used with three directions replacing the original eight directions: anterior (ANT), posteromedial (PM) and posterolateral (PL). Participants stood barefoot at the centre of the testing grid with hands on hips in bilateral stance. The non-supporting leg reached along the designated direction to the farthest distance point while maintaining balance with the supporting leg. Each direction was tested 3 times, with average values and Composite reach (CR) calculated.

Proprioceptive testing

Passive joint position sense was tested using the Biodex system. Three target angles were set at 30°, 45° and 60° knee flexion positions. Patients sat in the examination chair with blindfold, and the examiner moved the knee joint to the target angle at 2°/s angular velocity and held for 5 s before returning to the starting position. Participants independently controlled the joystick to reproduce the target angle. Each angle was tested 3 times, recording absolute values of angular errors.

Patient-reported outcomes

(1) IKDC Subjective Knee Assessment Form contains 10 questions with total score 0–100, higher scores indicating better knee function; (2) Lysholm Knee Scoring Scale contains 8 questions with total score 0–100, assessing knee symptoms and functional limitations; (3) ACL-RTS Index (ACL-RSI) contains 12 questions assessing psychological readiness for RTS, with higher scores indicating greater psychological preparedness.

Statistical analysis

Descriptive statistics presented continuous variables as mean ± standard deviation and categorical variables as frequencies and percentages. Normality testing used the Shapiro–Wilk test, and homogeneity of variance testing used Levene's test.

Baseline characteristic comparisons used independent samples *t*-tests (continuous variables) and Chi-square tests or Fisher's exact tests (categorical variables). Longitudinal changes were analysed using two-way repeated measures analysis of variance (two-way repeated measures analysis of variance), with time (pre-operative, 24 weeks and 48 weeks) as a within-subject factor and group (FRM vs. TRM) as a between-subject factor. When sphericity assumptions were violated (Mauchly's test, $P < 0.05$), Greenhouse–Geisser correction was applied. Significant interaction effects were examined through simple effects analysis, with multiple comparisons using Bonferroni correction.

RTS rate comparisons used Chi-square tests, calculating relative risk (RR), 95% confidence intervals (CIs) and Number needed to treat (NNT). Effect size calculations used Cohen's *d* (between-group comparisons) and partial eta squared (η^2, repeated measures analysis). Missing data were handled using multiple imputation methods. All analyses used IBM SPSS Statistics 28.0 (IBM Corp., Armonk, NY, USA), with significance level set at $P < 0.05$ (two-sided tests).

Results

Participant flow and baseline characteristics

Among 71 assessed patients, 64 met the inclusion criteria and completed randomisation (FRM group $n = 32$, TRM group $n = 32$). During follow-up, 7 participants withdrew (FRM group $n = 4$, TRM group $n = 3$), resulting in a final sample size of 57 participants (retention rate 89.1%) [Figure 1].

Baseline characteristics demonstrated excellent group comparability. The FRM group had a mean age of 27.3 ± 5.4 years compared to 28.6 ± 6.3 years in the TRM group ($P = 0.351$). Gender distribution showed 22 males (68.75%) in the FRM group and 19 males (59.38%) in the TRM group ($P = 0.440$). Body mass index was 23.8 ± 2.5 kg/m^2 in the FRM group and 22.7 ± 3.2 kg/m^2 in the TRM group ($P = 0.119$). Pre-operative knee function assessment revealed no significant differences between the groups for Lysholm, IKDC and Tegner scores (all $P > 0.05$) [Table 1].

Table 1: Baseline characteristic comparison of randomised participants (n=64)

Characteristic	FRM Group (n=32)	TRM Group (n=32)	Statistic	P
Demographic characteristics				
Age (years)	27.3±5.4	28.6±6.3	t=−0.94	0.351
Sex, n (%)				
Male	22 (68.75)	19 (59.38)	χ^2=0.60	0.440
Height (cm)	176.0±4.1	177.0±3.2	t=−1.04	0.302
Weight (kg)	73.4±6.3	71.2±9.1	t=1.13	0.263
BMI (kg/m^2), mean ± SD	23.8±2.5	22.7±3.2	t=1.58	0.119
Injured side, right, n (%)	20 (62.50)	18 (56.25)	χ^2=0.25	0.614
Surgery-related information				
Time from injury to surgery (weeks)	3.17±2.35	3.62±2.06	t=−0.84	0.404
Baseline function				
Lysholm	44.75±8.72	45.30±9.43	t=−0.25	0.805
IKDC	47.65±7.89	44.63±9.22	t=1.42	0.161
Tegner	6.2±1.2	6.3±1.3	t=−0.33	0.742

FRM: Functional rehabilitation model, TRM: Traditional rehabilitation model, BMI: Body mass index, SD: Standard deviation, IKDC: International Knee Documentation Committee

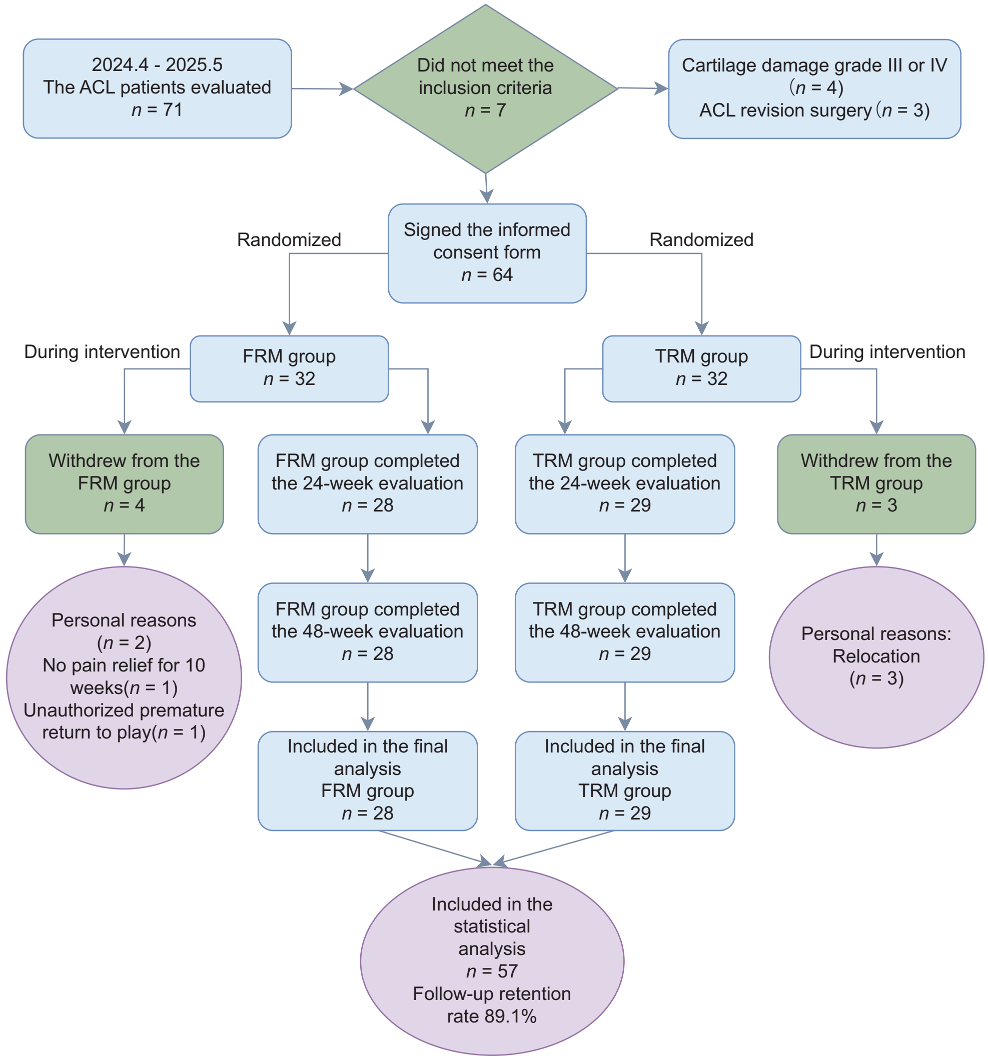

Figure 1: Design and flowchart of the study. ACL: Anterior cruciate ligament, FRM: Functional rehabilitation model, TRM: Traditional rehabilitation model

Primary outcomes

Return to sport rate

Assessment of RTS at 48 weeks demonstrated that the FRM group achieved a significantly higher successful RTS rate compared to the TRM group (89.3% [25/28] vs. 62.1% [18/29], χ^2 = 4.32, P = 0.038). The RR for the FRM group was 1.44 (95% CI: 1.05–1.97), indicating that patients receiving functional rehabilitation had a 44% higher likelihood of returning to sport compared to the TRM group. The NNT was 3.7 (95% CI: 2.1–14.7), signifying that for every 3.7 patients treated, one additional successful RTS would be achieved. Sensitivity analysis using Fisher's exact test maintained consistent results (two-tailed $P = 0.046$).

Functional recovery trajectory analysis

Repeated measures analysis of variance revealed significant time × group interaction effects for multiple key outcome measures, demonstrating that the FRM group exhibited superior recovery patterns characterised by linear sustained improvement, while the TRM group displayed a distinct recovery plateau after 24 weeks.

Secondary outcomes

Isokinetic strength testing results at 60°/s

Group-by-time interactions

Significant time × group interactions were observed for all isokinetic variables: extensor PT (F = 48.25, P < 0.001, ηp^2 = 0.47), PT/BW (F = 52.36, P < 0.001, ηp^2 = 0.49), TW (F = 47.15, P < 0.001, ηp^2 = 0.46), extensor LSI (F = 62.35, P < 0.001, ηp^2 = 0.53), flexor PT (F = 36.18, P < 0.001, ηp^2 = 0.45), flexor LSI (F = 55.47, P < 0.001, ηp^2 = 0.50) and H/Q ratio (F = 15.28, P < 0.001, ηp^2 = 0.26).

Post hoc analysis

Extensor strength

At 24 weeks, the TRM group declined to 76.85 ± 10.24 Nm (−14.3% from baseline, P < 0.001), while the FRM group improved to 102.36 ± 9.85 Nm (+17.3%, P < 0.001). At 48 weeks, the FRM group achieved 124.17 ± 7.25 Nm (+42.3%), significantly exceeding the TRM group's 98.42 ± 8.73 Nm (+9.8%) (difference: +25.75 Nm, P < 0.001).

Normalised strength (PT/BW)

The FRM group demonstrated superior recovery, reaching 167.92% ± 8.42% at 48 weeks compared to 129.15% ± 9.85% in the TRM group (difference: +38.77%, $P < 0.001$).

Limb symmetry index

The FRM group achieved near-complete symmetry restoration (89.15% ± 3.85%) while the TRM group reached only 69.45% ± 5.15% at 48 weeks (difference: +19.70%, $P < 0.001$).

Flexor strength

Significant main effects were found for time ($F = 53.74$, $P < 0.001$, $\eta p^2 = 0.62$) and group ($F = 29.85$, $P < 0.001$, $\eta p^2 = 0.35$). At 48 weeks, the FRM group achieved 72.64 ± 5.28 Nm versus 61.85 ± 5.42 Nm in the TRM group ($P < 0.001$). Flexor LSI recovery was superior in the FRM group (99.75% ± 3.25%) compared to TRM (83.35% ± 4.75%, $P < 0.001$).

Muscle balance

The H/Q ratio showed significant time ($F = 12.35$, $P < 0.001$, $\eta p^2 = 0.18$) and group effects ($F = 8.42$, $P = 0.005$, $\eta p^2 = 0.14$). The FRM group maintained stable ratios (48 weeks: 58.52% ± 3.85%), while the TRM group exhibited fluctuations (62.84% ± 4.25%).

The FRM group consistently outperformed the TRM group across all parameters, with effect sizes ranging from moderate to large ($\eta p^2 = 0.26$–0.62) [Table 2].

Single-leg hop test results

Within-group changes

Both the groups showed significant improvements from 24 to 48 weeks. Hop distance increased in the FRM (75.37 ± 18.14–102.48 ± 21.85 cm, $t = 5.42$, $P < 0.001$) and TRM groups (60.48 ± 31.27–89.73 ± 35.16 cm, $t = 4.72$, $P < 0.001$). Lateral hop time improved in the FRM (8.79 ± 4.54–5.54 ± 2.25 s, $t = 4.25$, $P < 0.001$) and TRM groups (10.06 ± 4.68–7.84 ± 3.37 s, $t = 3.12$, $P = 0.004$). Box hop time improved significantly in the FRM group (10.23 ± 6.26–6.34 ± 3.06 s, $t = 3.56$, $P = 0.001$) but not TRM group (11.58 ± 7.49–9.42 ± 5.27 s, $t = 1.79$, $P = 0.084$).

Limb symmetry index

LSI improved significantly in both the groups across all measures. Hop distance LSI: FRM 71.90% ± 22.86% to 93.20% ± 31.20% ($t = 3.81$, $P < 0.001$); TRM 57.10% ± 31.98% to 82.80% ± 31.80% ($t = 4.32$, $P < 0.001$). Lateral hop LSI: FRM 67.30% ± 31.90% to 96.00% ± 35.90% ($t = 4.21$, $P < 0.001$); TRM 56.10% ± 27.00% to 69.80% ± 26.50% ($t = 2.62$, $P = 0.014$). Box hop LSI: FRM 61.90% ± 36.40% to 97.50% ± 29.60% ($t = 5.25$, $P < 0.001$); TRM 64.10% ± 27.30% to 76.20% ± 31.40% ($t = 2.13$, $P = 0.042$).

Between-group comparisons

At 48 weeks, the FRM group demonstrated superior performance in lateral hop time (5.54 ± 2.25 vs. 7.84 ± 3.37 s, $t = 3.04$, $P = 0.004$), lateral hop LSI (96.00% ± 35.90% vs. 69.80% ± 26.50%, $t = 3.13$, $P = 0.003$), box hop time (6.34 ± 3.06 vs. 9.42 ± 5.27 s, $t = 2.71$, $P = 0.009$) and box hop LSI (97.50% ± 29.60% vs. 76.20% ± 31.40%, $t = 2.64$, $P = 0.011$). No significant differences were found for hop distance ($t = 1.65$, $P = 0.105$) or hop distance LSI ($t = 1.25$, $P = 0.218$) [Table 3].

Dynamic balance test results (modified star excursion balance test)

Within-group changes

No significant within-group improvements were observed from 24 to 48 weeks in either group across all directions (all $P > 0.341$). ANT: FRM 65.7 ± 4.8–66.9 ± 4.3 cm ($t = -0.808$, $P = 0.430$); TRM 60.2 ± 5.5–62.1 ± 5.0 cm ($t = -0.589$, $P = 0.563$). PM: FRM 113.6 ± 8.5–115.5 ± 6.3 cm ($t = -0.568$, $P = 0.576$); TRM 106.8 ± 9.1–110.3 ± 7.2 cm ($t = -0.954$, $P = 0.352$). PL: FRM 111.1 ± 7.2–110.9 ± 6.2 cm ($t = 0.067$, $P = 0.947$); TRM 104.5 ± 8.3–106.7 ± 7.0 cm ($t = -0.641$, $P = 0.529$). CR:

Table 2: Repeated measures analysis of variance for isokinetic strength at 60°/s (2×3) at 48 weeks

Indicator	Group	Pre-operative	24 weeks	48 weeks	Time (*F*, *P*)	Group (*F*, *P*)	Time × Group (*F*, *P*)
Extensor PT (Nm)	TRM	89.63±11.52	76.85±10.24[a]	98.42±8.73[a, b]	68.42, <0.001	35.17, <0.001	48.25, <0.001
	FRM	87.28±9.37	102.36±9.85[a, c]	124.17±7.25[a, b, c]			
Extensor PT/BW (%)	TRM	123.54±12.32	106.84±11.37[a]	129.15±9.85[b]	72.15, <0.001	41.83, <0.001	52.36, <0.001
	FRM	121.20±10.79	139.85±11.24[a, c]	167.92±8.42[a, b, c]			
Extensor TW (J)	TRM	445.27±49.53	380.45±46.28[a]	530.84±39.62[a, b]	65.28, <0.001	38.42, <0.001	47.15, <0.001
	FRM	441.07±48.27	512.37±45.16[a, c]	642.85±36.73[a, b, c]			
Flexor PT (Nm)	TRM	49.95±4.70	52.36±5.27	61.85±5.42[a, b]	53.74, <0.001	29.85, <0.001	36.18, <0.001
	FRM	47.39±6.27	58.73±6.15[a, c]	72.64±5.28[a, b, c]			
Extensor LSI (%)	TRM	63.67±3.58	54.07±4.25[a]	69.45±5.15[a, b]	76.84, <0.001	48.17, <0.001	62.35, <0.001
	FRM	62.35±4.68	73.85±4.75[a, c]	89.15±3.85[a, b, c]			
H/Q (%)	TRM	55.73±2.92	68.15±3.85[a]	62.84±4.25[a, b]	12.35, <0.001	8.42, 0.005	15.28, <0.001
	FRM	54.30±5.23	57.38±5.15	58.52±3.85			

[a]Significant difference compared with pre-operative value ($P < 0.05$), [b]Significant difference compared with 6-month post-operative value ($P < 0.05$), [c]Significant difference compared with TRM group at the same time point ($P < 0.05$). FRM: Functional rehabilitation model, TRM: Traditional rehabilitation model, LSI: Limb symmetry index, PT: Peak torque, TW: Total work, BW: Body weight

FRM 96.8 ± 4.0–97.8 ± 3.3 (t = −0.610, P = 0.550); TRM 90.5 ± 6.3–93.0 ± 5.1 (t = −0.975, P = 0.341).

Between-group comparisons

At 24 weeks, the FRM group demonstrated superior performance across all measures: ANT (65.7 ± 4.8 vs. 60.2 ± 5.5 cm, t = −3.56, P = 0.001), PM (113.6 ± 8.5 vs. 106.8 ± 9.1 cm, t = −3.44, P = 0.002), PL (111.1 ± 7.2 vs. 104.5 ± 8.3 cm, t = −3.28, P = 0.003) and CR (96.8 ± 4.0 vs. 90.5 ± 6.3, t = −3.67, P = 0.001).

At 48 weeks, the FRM group maintained significant advantages in ANT (66.9 ± 4.3 vs. 62.1 ± 5.0 cm, t = 2.382, P = 0.028) and CR (97.8 ± 3.3 vs. 93.0 ± 5.1, t = 2.669, P = 0.016). PM (115.5 ± 6.3 vs. 110.3 ± 7.2 cm, t = 1.727, P = 0.101) and PL (110.9 ± 6.2 vs. 106.7 ± 7.0 cm, t = 1.90, P = 0.074) showed numerical superiority but failed to reach statistical significance [Table 4].

Proprioception test results

Group-by-time interactions

Significant main effects for time were observed across all knee flexion angles: 30° (F = 10.52, P < 0.001, η^2 = 0.158), 45° (F = 5.32, P = 0.006, η^2 = 0.087) and 60° (F = 15.86, P < 0.001, η^2 = 0.221). Significant time × group interactions were found at 30° (F = 7.85, P = 0.001, η^2 = 0.123) and 45° (F = 12.43, P < 0.001, η^2 = 0.182), but not at 60° (F = 3.01, P = 0.053, η^2 = 0.051).

Between-group comparisons

At 48 weeks, the FRM group demonstrated superior proprioceptive accuracy compared to the TRM group. Position sense errors were significantly lower in the FRM group at 30° flexion (2.83° ± 1.63° vs. 4.25° ± 1.85°, t = 3.25, P = 0.002, Cohen's d = 0.85) and 45° flexion (6.37° ± 1.69° vs. 7.57° ± 1.73°, t = 2.77, P = 0.008, Cohen's d = 0.72). At 60° flexion, no significant between-group difference was observed (6.47° ± 2.07° vs. 7.78° ± 5.46°, P > 0.05).

Recovery patterns

The FRM group exhibited continuous linear improvement throughout the 48-week period, achieving improvement rates of 39.4% (30°), 14.0% (45°) and 34.9% (60°) compared to pre-operative values. In contrast, the TRM group plateaued after 24 weeks, with final improvement rates of only 18.7% (30°), 4.5% (45°) and 16.7% (60°).

Both the groups showed significant improvements from baseline at 24 weeks across all angles. However, only the FRM group demonstrated continued improvement from 24 to 48 weeks, particularly at 30° and 45° flexion angles [Table 5].

Table 3: Comparison of Hop-test results at 48 weeks

Variable	Group	24 weeks	48 weeks	Within-Group (t, P)	Between-Group at 24 weeks (t, P)	Between-Group at 48 weeks (t, P)
Single-leg hop (cm)	TRM	60.48±31.27	89.73±35.16	4.72, <0.001	2.21, 0.031	1.65, 0.105
	FRM	75.37±18.14	102.48±21.85	5.42, <0.001		
Single-leg hop LSI (%)	TRM	57.10±31.98	82.80±31.80	4.32, <0.001	2.02, 0.048	1.25, 0.218
	FRM	71.90±22.86	93.20±31.20	3.81, <0.001		
Single-leg lateral hop (s)	TRM	10.06±4.68	7.84±3.37	3.12, 0.004	1.04, 0.303	3.04, 0.004
	FRM	8.79±4.54	5.54±2.25	4.25, <0.001		
Lateral hop LSI (%)	TRM	56.10±27.00	69.80±26.50	2.62, 0.014	1.43, 0.159	3.13, 0.003
	FRM	67.30±31.90	96.00±35.90	4.21, <0.001		
Single-leg box hop (s)	TRM	11.58±7.49	9.42±5.27	1.79, 0.084	0.74, 0.463	2.71, 0.009
	FRM	10.23±6.26	6.34±3.06	3.56, 0.001		
Box hop LSI (%)	FRM	61.90±36.40	97.50±29.60	5.25, <0.001	0.26, 0.798	2.64, 0.011
	TRM	64.10±27.30	76.20±31.40	2.13, 0.042		

FRM: Functional rehabilitation model, TRM: Traditional rehabilitation model, LSI: Limb symmetry index

Table 4: Comparison of modified star excursion balance test results at 48 weeks

Variable	Group	24 weeks	48 weeks	Within-Group (t, P)	Between-Group at 24 weeks (t, P)	Between-Group at 48 weeks (t, P)
ANT	TRM	60.2±5.5	62.1±5.0	−0.589, 0.563	−3.56, 0.001	2.382, 0.028
	FRM	65.7±4.8	66.9±4.3	−0.808, 0.430		
PM	TRM	106.8±9.1	110.3±7.2	−0.954, 0.352	−3.44, 0.002	1.727, 0.101
	FRM	113.6±8.5	115.5±6.3	−0.568, 0.576		
PL	TRM	104.5±8.3	106.7±7.0	−0.641, 0.529	−3.28, 0.003	1.90, 0.074
	FRM	111.1±7.2	110.9±6.2	0.067, 0.947		
CR	TRM	90.5±6.3	93.0±5.1	−0.975, 0.341	−3.67, 0.001	2.669, 0.016
	FRM	96.8±4.0	97.8±3.3	−0.610, 0.550		

FRM: Functional rehabilitation model, TRM: Traditional rehabilitation model, PL: Posterolateral, PM: Posteromedial, ANT: Anterior, CR: Composite scores

Table 5: Repeated measures analysis of variance results of proprioception test at 48 weeks (2 × 3 design)

Variable PJPS (°)	Group	Pre-operative	24 weeks	48 weeks	Time (F, P, η^2)	Group (F, P, η^2)	Time × Group (F, P, η^2)
Knee flexion 30°	TRM	5.23±2.94	4.12±2.17[a]	4.25±1.85[a]	10.52, <0.001, 0.158	3.12, 0.083, 0.053	7.85, 0.001, 0.123
	FRM	4.67±3.25	3.87±2.03[a]	2.83±1.63[a,b,c]			
Knee flexion 45°	TRM	7.93±2.13	7.18±1.78[a]	7.57±1.73[b]	5.32, 0.006, 0.087	5.07, 0.028, 0.083	12.43, 0.001, 0.182
	FRM	7.41±2.52	6.92±1.74	6.37±1.69[a,c]			
Knee flexion 60°	TRM	9.34±3.24	8.26±2.52[a]	7.78±5.46	15.86, <0.001, 0.221	7.25, 0.009, 0.115	3.01, 0.053, 0.051
	FRM	8.41±3.51	7.82±2.38[a]	6.47±2.07[a,b]			

[a]Significant difference compared to pre-operation ($P < 0.05$), [b]Significant difference compared to 24 weeks post-operation ($P < 0.05$), [c]Significant difference compared to TRM group at the same time point ($P < 0.05$). FRM: Functional rehabilitation model, TRM: Traditional rehabilitation model, PJPS: Passive joint position sense

Table 6: Patient-reported outcomes

Index	Group	Pre-surgery	24 weeks	48 weeks	Time effect (F, P, η^2)	Group effect (F, P, η^2)	Time x Group interaction (F, P, η^2)
IKDC	TRM	42.10±10.25	68.24±10.21[a]	83.45±12.73[a, b]	412.58, <0.001, 0.883	28.75, 0.001, 0.346	53.31, 0.001, 0.675
	FRM	43.25±6.58	82.45±7.30[a, c]	89.45±9.72[a, b, c]			
Lysholm	TRM	45.30±9.43	67.38±11.92[a]	76.12±12.38[a, b]	312.42, <0.001, 0.85	24.17, 0.001, 0.305	32.19, 0.003, 0.369
	FRM	44.75±8.72	75.35±7.52[a, c]	88.71±5.78[a, b, c]			
ACL-RSI	TRM	44.63±9.22	64.16±12.37[a]	70.35±10.24[a, b]	214.73, 0.001, 0.796	9.84, 0.003, 0.152	6.9, 0.003, 0.111
	FRM	47.65±7.89	71.43±9.62[a, c]	79.52±8.17[a, b, c]			

[a]Significant difference compared to pre-surgery ($P < 0.05$), [b]Significant difference compared to 6 months post-surgery ($P < 0.05$), [c]Significant difference compared to TRM group at the same time point ($P < 0.05$). FRM: Functional rehabilitation model, TRM: Traditional rehabilitation model, ACL: Anterior cruciate ligament, RSI: Return to sport index, IKDC: International Knee Documentation Committee

Patient-reported outcomes

Group-by-time interactions

Significant time × group interactions were observed for all patient-reported measures: IKDC (F = 53.31, P < 0.001, η^2 = 0.675), Lysholm (F = 32.19, P = 0.003, η^2 = 0.369) and ACL-RSI (F = 6.90, P = 0.003, η^2 = 0.111). All measures demonstrated significant main effects for time (F = 214.73–412.58, all P < 0.001) and group (F = 9.84–28.75, all $P \leq 0.003$).

Recovery patterns

International Knee Documentation Committee scores

The FRM group exhibited continuous linear improvement: 43.25 ± 6.58 (pre-surgery) to 82.45 ± 7.30 (24 weeks) to 89.45 ± 9.72 (48 weeks), with significant improvement from 24 to 48 weeks (t = −7.2, P < 0.001, Cohen's d = 0.82). The TRM group showed 42.10 ± 10.25 to 68.24 ± 10.21 to 83.45 ± 12.73, with slower late-phase improvement (t = −8.9, P < 0.001, Cohen's d = 1.42).

Lysholm scores

The FRM group demonstrated sustained improvement: 44.75 ± 8.72 to 75.35 ± 7.52 to 88.71 ± 5.78. The TRM group plateaued in the later phase: 45.30 ± 9.43 to 67.38 ± 11.92 to 76.12 ± 12.38.

Anterior Cruciate Ligament-Return to Sport after Injury scores

The FRM group maintained linear improvement: 47.65 ± 7.89 to 71.43 ± 9.62 to 79.52 ± 8.17, with continued significant improvement from 24 to 48 weeks (t = −5.42, P < 0.001, Cohen's d = 0.91). The TRM group showed attenuated late-phase improvement: 44.63 ± 9.22 to 64.16 ± 12.37 to 70.35 ± 10.24.

Between-group comparisons

At 48 weeks, the FRM group demonstrated superior outcomes across all measures: IKDC (89.45 ± 9.72 vs. 83.45 ± 12.73, t = 6.25, P = 0.028, Cohen's d = 0.58), Lysholm (88.71 ± 5.78 vs. 76.12 ± 12.38, t = 5.07, P < 0.001, Cohen's d = 1.58) and ACL-RSI (79.52 ± 8.17 vs. 70.35 ± 10.24, t = 3.78, P < 0.001, Cohen's d = 0.99) [Table 6].

Discussion

This prospective randomised controlled trial systematically validated the significant advantages of FRM in the rehabilitation of HSDs following ACLR. The FRM group achieved significantly higher RTS success rates compared to the TRM group, with clinically meaningful effect sizes. This study provides important evidence-based guidance for ACL rehabilitation practice.

Neurobiological advantages of functional rehabilitation model

The core advantage of FRM lies in its promotion of corticospinal pathway reorganisation. Kapreli *et al*.[11]

demonstrated that ACL-injured patients exhibit altered cortical activation patterns. Grooms *et al*.[21] revealed that functional training significantly improves corticospinal connection strength, particularly in pre-motor and primary motor cortical regions. This correlates with the linear improvement pattern observed in the FRM group during the 24–48-week period. In contrast, traditional rehabilitation primarily activates spinal-level neural circuits with limited cortical activation,[22] explaining the recovery plateau observed in the TRM group.

FRM systematically rebuilt the sensorimotor integration system through multimodal sensory training.[23] Unstable surface training provided rich proprioceptive stimulation, activating mechanoreceptors throughout the lower extremity kinetic chain. Vibration training enhanced muscle spindle sensitivity, while eye-closed balance training promoted sensory reweighting.[24] The FRM group's superior proprioceptive accuracy directly reflects this multimodal reconstruction strategy's effectiveness, which is crucial for motor control and injury prevention.[25]

FRM rebuilt adaptive motor control through progressive functional challenges.[10] Early closed-chain training established feedforward control patterns, mid-stage unstable surface training developed feedback control systems and late-stage sport-specific training integrated both systems for optimal performance in complex environments.[10] The FRM group's sustained advantage in dynamic balance testing directly reflects this adaptive control strategy's effectiveness.

Biomechanical mechanisms of muscle strength and functional recovery

The isokinetic strength testing demonstrated significant FRM advantages, with superior recovery in quadriceps PT, normalised strength and limb symmetry indices. High-load functional training activates mechanistic target of rapamycin signalling pathways, promoting muscle hypertrophy and protein synthesis.[26] Snyder-Mackler *et al*.[27] demonstrated that functional training more effectively activates fast-twitch muscle fibres crucial for explosive power. From a neural perspective, FRM improved motor unit recruitment and reduced arthrogenic muscle inhibition.[28]

HS strength recovery holds special significance for ACL reconstruction. The FRM group achieved near-complete symmetry recovery, substantially exceeding the TRM group. Research demonstrates that HS strength improvements correlate with reduced ACL injury risk.[29] Maintenance of appropriate H/Q ratios is crucial for dynamic knee stability and ACL graft protection.[30]

Integrative assessment of functional movement performance

Single-leg hop tests reflect athletes' real-world performance capabilities. The FRM group exhibited significant advantages in tests requiring rapid direction changes and stability control, reflecting superior multi-planar movement control and rapid stabilisation capabilities crucial for complex motor skill execution.[31] Superior three-dimensional jump-landing control directly relates to injury risk reduction.[32]

In dynamic balance testing, the FRM group maintained stability at significantly higher levels. The advantages in critical movement directions reflect superior motor control system integration, requiring coordinated ankle mobility, knee stability and hip control.[33]

Psychosocial factors and return to sport confidence

Patient-reported outcomes reflect FRM's psychological rehabilitation advantages. The FRM group's sustained ACL-RSI improvement demonstrates systematic confidence rebuilding through progressive functional challenges. Based on self-efficacy theory, mastery experiences most effectively build confidence.[34] FRM systematically broke the pain-fear-avoidance cycle by gradually introducing challenging movements in controlled environments.

IKDC and Lysholm results further supported FRM's advantages, demonstrating benefits in both objective functional parameters and subjective patient experience.[35]

Repeated measures analysis revealed complex temporal dynamics of ACL post-operative recovery. Early stages showed functional declines reflecting surgical trauma and activity restrictions, including arthrogenic muscle inhibition and disuse atrophy.[36] Mid-term stages showed distinct between-group differences. The FRM group exhibited sustained linear improvement, while the TRM group showed plateau phenomena. This difference reflects superior neuroplasticity activation in FRM.[37]

Clinical practice significance and implementation considerations

This study provides high-quality evidence for ACL post-operative rehabilitation. FRM, as a comprehensive strategy based on neuroscience, biomechanics and psychological principles, should become standard treatment for high sports demand populations. The NNT of 3.7 indicates good clinical benefit.

Although FRM demonstrates overall advantages, individualised factors require consideration. Patient age, gender, athletic level, concomitant injuries and psychological status may influence outcomes. Future research should explore these interactions to develop more precise individualised strategies.[38]

Research strengths and limitations

This study has several limitations. First, as a single-centre study, external validity may be limited, and multicentre studies would help validate generalisability. Second, while the 48-week follow-up was relatively long, it remains insufficient for evaluating long-term reinjury risk and joint health.

Additionally, this study primarily focused on functional outcomes, lacking direct measurement of underlying biological mechanisms. Future research should integrate imaging, biomarkers and neurophysiological parameters to better understand FRM mechanisms of action.

Conclusion

This prospective randomised controlled trial demonstrated that FRM significantly outperformed TRM in HSDs following ACLR across multiple outcome domains. The FRM group achieved higher RTS rates, superior isokinetic strength recovery, better dynamic balance, improved proprioceptive accuracy and greater psychological readiness. The sustained linear improvement pattern observed in the FRM group, contrasting with the TRM group's recovery plateau after 24 weeks, underscores the importance of neuromuscular control training and sport-specific conditioning. These findings support adopting FRM as the preferred rehabilitation approach for HSDs following ACLR.

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Conflicts of interest

There are no conflicts of interest.

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