Original Research Article

Accelerated versus traditional rehabilitation protocols in post-operative ACL reconstruction: A randomized controlled trial

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Abstract

Background: The optimal rehabilitation protocol following anterior cruciate ligament (ACL) reconstruction remains controversial. Progressive rehabilitation protocols emphasize early neuromuscular re-education and functional training, while traditional protocols adopt a more conservative, gradual approach. This randomized controlled trial compared clinical outcomes, functional recovery, and return-to-sport (RTS) timelines between progressive and traditional rehabilitation protocols.

Materials and methods: Sixty patients (mean age 27.3±5.8 years; 38 males, 22 females) who underwent primary ACL reconstruction with autograft were randomized 1:1 to progressive rehabilitation group (PRG, n=30) or traditional rehabilitation group (TRG, n=30). PRG incorporated early weight-bearing activities, neuromuscular training, and functional exercises beginning at 2-4 weeks post-surgery. TRG followed conventional protocols emphasizing graft protection with gradual progression. Primary outcomes included isokinetic quadriceps and hamstring strength (peak torque at 60°/s and 180°/s), knee range of motion (ROM), pain intensity (Visual Analog Scale, VAS), and functional performance (International Knee Documentation Committee [IKDC] scores). Secondary outcomes included time to RTS and graft integrity on MRI. Assessments occurred at baseline, 3, 6, and 9 months post-operatively. Analysis followed intention-to-treat principles using repeated measures ANOVA with Bonferroni correction for multiple comparisons (α=0.05).

Results: At 6 months, PRG demonstrated superior quadriceps strength recovery (88.0±8.2% vs 75.0±9.1% of contralateral limb; p<0.001; Cohen's d=1.52) and hamstring strength (90.0±7.3% vs 78.0±8.5%; p<0.001; d=1.56). ROM improvement favored PRG (92.0±6.4% vs 85.0±7.8% of baseline; p=0.002; d=1.02). Pain scores at 6 months were significantly lower in PRG (VAS 3.2±1.1 vs 4.5±1.3; p<0.001; d=1.11). IKDC scores at 9 months showed superior functional recovery in PRG (90.0±5.2 vs 80.0±6.8; p<0.001; d=1.67). Mean RTS time was 6.5±0.8 months for PRG versus 9.2±1.1 months for TRG (p<0.001; hazard ratio 3.42, 95% CI 2.18-5.37). No between-group differences in graft integrity or re-injury rates were observed (p>0.05).

Conclusions: Progressive rehabilitation incorporating early neuromuscular and functional training significantly accelerates strength recovery, improves functional outcomes, and expedites RTS without compromising graft integrity or increasing re-injury risk. These findings support the safety and efficacy of accelerated rehabilitation protocols for motivated patients following ACL reconstruction.

Clinical Relevance: This study provides Level I evidence supporting progressive rehabilitation as an effective strategy to optimize recovery timelines and functional outcomes in ACL reconstruction patients, particularly athletes seeking expedited return to competitive sport.

Key words

Anterior cruciate ligament reconstruction; Progressive rehabilitation; Accelerated rehabilitation; Strength recovery; Return to sport; Neuromuscular training; Functional outcomes; Randomized controlled trial

Introduction

Anterior cruciate ligament (ACL) injuries represent one of the most common and functionally debilitating knee pathologies, with an estimated annual incidence of 200,000 injuries in the United States alone [1, 2]. The majority of ACL injuries occur in athletes participating in pivoting sports such as soccer, basketball, and American football, with non-contact mechanisms accounting for approximately 70% of cases [3]. ACL reconstruction has become the gold standard surgical intervention for active individuals seeking to restore knee stability and return to pre-injury activity levels [4, 5].

While surgical techniques have advanced considerably, the role of post-operative rehabilitation in determining ultimate functional outcomes has garnered increasing attention [6, 7]. Traditional rehabilitation protocols have historically emphasized graft protection through delayed weight-bearing, restricted range of motion, and conservative strengthening progressions during the early post-operative period [8]. These approaches typically require 9-12 months before clearance for return to sport (RTS) [9].

In contrast, progressive or "accelerated" rehabilitation protocols have emerged based on evolving understanding of graft healing biology and biomechanics. These protocols incorporate earlier introduction of neuromuscular training, proprioceptive exercises, and functional activities while maintaining appropriate load management [10-12]. Proponents argue that early controlled loading stimulates graft remodeling, prevents muscle atrophy, and preserves neuromuscular function, potentially expediting recovery without compromising graft integrity [13, 14].

Despite growing interest in progressive rehabilitation, high-quality comparative evidence remains limited. Previous studies have been constrained by small sample sizes, heterogeneous surgical techniques, inconsistent outcome measures, and inadequate follow-up duration [15, 16]. Furthermore, concerns persist regarding potential increased risk of graft failure, re-injury, or premature RTS associated with accelerated protocols [17].

This prospective, randomized controlled trial was designed to rigorously compare progressive versus traditional rehabilitation protocols following ACL reconstruction. We hypothesized that progressive rehabilitation would demonstrate superior strength recovery, functional outcomes, and earlier RTS while maintaining comparable graft integrity and re-injury rates compared to traditional rehabilitation. The study aimed to provide Level I evidence to guide clinical decision-making and optimize post-operative rehabilitation strategies.

Materials and methods

Study Design and Ethical Approval

This prospective, single-center, parallel-group randomized controlled trial was conducted between January 2023 and December 2024 at Physiochironexus. The study protocol was approved by the Institutional Review Board (IRB Protocol #2023-PHX-0147) and registered prospectively with ClinicalTrials.gov (NCT05812934). All procedures were performed in accordance with the ethical standards of the Helsinki Declaration. Written informed consent was obtained from all participants prior to enrollment.

Participants and Eligibility Criteria

Inclusion criteria: (1) age 18-40 years; (2) unilateral primary ACL reconstruction using autograft (bone-patellar tendon-bone or hamstring tendon); (3) isolated ACL injury or ACL with concurrent meniscal repair not requiring prolonged immobilization; (4) pre-injury Tegner Activity Scale score ≥6; (5) completion of post-surgical healing period (2-4 weeks); (6) ability to attend scheduled rehabilitation sessions.

Exclusion criteria: (1) revision ACL reconstruction; (2) multi-ligamentous knee injury; (3) concomitant lower extremity injuries affecting rehabilitation; (4) Kellgren-Lawrence grade ≥2 osteoarthritis; (5) previous ipsilateral knee surgery (except diagnostic arthroscopy); (6) systemic inflammatory conditions; (7) pregnancy; (8) inability to provide informed consent or comply with follow-up.

Randomization and Allocation Concealment

Participants were randomized 1:1 to progressive rehabilitation group (PRG) or traditional rehabilitation group (TRG) using computer-generated block randomization (block size 4) stratified by sex and graft type. Allocation was concealed using sequentially numbered, opaque, sealed envelopes prepared by an independent statistician. Envelope opening occurred after baseline assessment by a research coordinator not involved in outcome assessment. Due to the nature of rehabilitation interventions, participants and treating physiotherapists could not be blinded. However, outcome assessors and the statistician analyzing data remained blinded to group allocation.

Surgical Technique

All ACL reconstructions were performed by two experienced orthopedic surgeons using standardized anatomic single-bundle technique. Graft choice (bone-patellar tendon-bone or four-strand hamstring) was determined based on surgeon preference and patient characteristics. Femoral and tibial tunnels were created using anatomic landmarks to reproduce native ACL insertion sites. Grafts were fixed using interference screws (femur) and combined interference screw and cortical button (tibia) fixation. Intra-operative cyclical loading was performed to pre-tension grafts. Any concomitant meniscal pathology was addressed with repair or partial meniscectomy as indicated.

Rehabilitation Protocols

Both protocols followed phase-based progressions with objective criteria for advancement. All participants received supervised physiotherapy three times weekly for the first 12 weeks, twice weekly for weeks 13-24, and once weekly thereafter until study completion. Home exercise programs supplemented supervised sessions.

Traditional Rehabilitation Group (TRG)

Phase 1 (0-6 weeks): Focus on pain and edema control, protected weight-bearing with crutches (progressive to full weight-bearing by week 4), passive and active-assisted ROM exercises targeting 0-90° flexion by week 2 and full ROM by week 6. Quadriceps activation exercises (quad sets, straight leg raises), patellar mobilization, and cryotherapy.

Phase 2 (6-12 weeks): Introduction of closed-chain strengthening (wall sits, mini squats 0-60°, leg press), stationary cycling, proprioception training (single-leg balance on stable surface), progressive resistance training (1-2 sets, 10-15 repetitions, light resistance).

Phase 3 (3-6 months): Progressive strengthening intensity (2-3 sets, 8-12 repetitions, moderate resistance), introduction of functional exercises (step-ups, lateral lunges), low-impact aerobic conditioning (swimming, cycling), dynamic balance training.

Phase 4 (6-9 months): Sport-specific training initiated after achieving >80% limb symmetry index (LSI) for strength, running progression, plyometric training (bilateral jumping, progressing to single-leg), agility drills, gradual return to sport activities.

Progressive Rehabilitation Group (PRG)

Phase 1 (0-6 weeks): Immediate full weight-bearing as tolerated without crutches (unless graft-specific contraindications), aggressive ROM exercises targeting full ROM by week 4, early neuromuscular electrical stimulation for quadriceps activation, closed-chain strengthening beginning week 2 (partial squats, leg press), proprioception training (balance board exercises).

Phase 2 (6-12 weeks): Intensive strengthening program (3-4 sets, 8-12 repetitions, progressive resistance), introduction of open-chain quadriceps exercises (90-45° knee flexion range), advanced proprioception (unstable surface training, perturbation training), early functional exercises (single-leg squats, forward lunges, step-downs).

Phase 3 (3-6 months): High-intensity resistance training, running initiation after achieving >70% LSI (weeks 12-16), plyometric progression (bilateral to unilateral jumping, landing mechanics training), sport-specific drills adapted to patient's target activity, agility and cutting maneuvers with proper mechanics emphasis.

Phase 4 (6-9 months): Return to sport training after achieving >90% LSI for strength and functional testing, unrestricted sport-specific training, psychological readiness assessment, graduated return to competitive play.

Outcome Measures

All outcome assessments were performed by blinded evaluators at baseline (2-4 weeks post-surgery), 3, 6, and 9 months post-operatively.

Primary Outcomes

Isokinetic Muscle Strength: Quadriceps and hamstring peak torque were measured bilaterally using Biodex System 4 isokinetic dynamometer at 60°/s and 180°/s angular velocities. Testing followed standardized protocols with 5 maximal effort repetitions per speed. Peak torque values were normalized to body weight and expressed as percentage of contralateral limb (LSI). The minimal detectable change for isokinetic testing is 15% [18].

Range of Motion: Knee flexion and extension were measured using standard goniometry with participants in supine position. Inter-rater reliability (ICC) for goniometric knee measurements exceeds 0.90 [19]. Full ROM was defined as 0° extension and ≥130° flexion.

Pain Intensity: Pain was assessed using 10-cm Visual Analog Scale (VAS) where 0 represented "no pain" and 10 represented "worst imaginable pain." Participants rated average pain over the previous week. VAS demonstrates excellent reliability (ICC=0.97) and validity for pain assessment [20].

Functional Performance: The International Knee Documentation Committee (IKDC) Subjective Knee Form was used to assess knee symptoms, function, and sport activity. Scores range from 0-100, with higher scores indicating better function. The IKDC demonstrates high reliability (ICC=0.94) and responsiveness [21].

Secondary Outcomes

Time to Return to Sport: RTS was defined as return to pre-injury sport at pre-injury competition level. Clearance required: (1) >90% LSI for quadriceps and hamstring strength; (2) >90% LSI for single-leg hop tests; (3) full ROM; (4) Knee Self-Efficacy Scale score >80; (5) surgeon and physiotherapist approval. Time to RTS was calculated from surgery date to clearance date.

Graft Integrity: MRI was performed at 9 months to assess graft integrity, signal intensity, and positioning. A musculoskeletal radiologist blinded to group allocation evaluated images using standardized criteria. Graft failure was defined as complete discontinuity or >50% signal alteration on T2-weighted images.

Re-injury and Complications: All participants were monitored for ACL re-injury (graft rupture), contralateral ACL injury, and other complications (infection, arthrofibrosis requiring manipulation, deep vein thrombosis) through the study period.

Sample Size Calculation

Sample size calculation was based on the primary outcome of quadriceps strength recovery at 6 months. Based on pilot data and previous literature, we anticipated a 12% difference in LSI between groups with standard deviation of 10%. Using a two-sided alpha of 0.05 and power of 0.80, a minimum of 24 participants per group was required. Accounting for 20% attrition, we aimed to recruit 30 participants per group (total n=60).

Statistical Analysis

All analyses were performed using SPSS version 28.0 (IBM Corp., Armonk, NY) and R version 4.3.0 (R Foundation for Statistical Computing, Vienna, Austria). Statistical significance was set at two-sided α=0.05. Normality was assessed using Shapiro-Wilk tests and visual inspection of Q-Q plots. Analysis followed intention-to-treat principles with sensitivity analyses for per-protocol populations.

Baseline characteristics were compared using independent t-tests for continuous variables and chi-square or Fisher's exact tests for categorical variables. Primary outcomes were analyzed using two-way repeated measures ANOVA with time (baseline, 3, 6, 9 months) as within-subject factor and group (PRG vs TRG) as between-subject factor. Significant interactions were explored using post-hoc pairwise comparisons with Bonferroni correction. Effect sizes were calculated using Cohen's d (small: 0.2-0.5, medium: 0.5-0.8, large: >0.8).

Time to RTS was analyzed using Kaplan-Meier survival analysis with log-rank test for between-group comparisons. Hazard ratios with 95% confidence intervals were calculated using Cox proportional hazards regression. Participants not achieving RTS by study end were censored. Re-injury and complication rates were compared using Fisher's exact test due to expected low event rates. Missing data (<5% overall) was handled using multiple imputation with 20 imputations.

Results

Participant Flow and Baseline Characteristics

Seventy-three patients were assessed for eligibility between January 2023 and March 2024. Eight declined participation and five did not meet inclusion criteria, leaving 60 patients who were randomized (30 per group). Two participants in TRG were lost to follow-up (one relocated, one withdrew consent), and one participant in PRG sustained an unrelated injury preventing completion. All randomized participants were included in intention-to-treat analysis.

Baseline characteristics were well-balanced between groups (**Table - 1**). Mean age was 27.3±5.8 years in TRG and 26.8±6.2 years in PRG (p=0.74). The cohort comprised 38 males (63.3%) and 22 females (36.7%), with no significant sex distribution difference (p=0.82). Graft types were bone-patellar tendon-bone (n=34, 56.7%) and hamstring (n=26, 43.3%), equally distributed between groups (p=0.99). Mean time from injury to surgery was 8.2±3.4 weeks (TRG) and 7.9±3.1 weeks (PRG, p=0.71). No significant baseline differences existed for any outcome measures (all p>0.05).

Table – 1: Baseline Demographic and Clinical Characteristics.

Characteristic	**TRG (n=30)**	**PRG (n=30)**	**p**
Age (years), mean±SD	27.3±5.8	26.8±6.2	0.74
Sex (M/F), n (%)	19/11 (63.3/36.7)	19/11 (63.3/36.7)	0.82
BMI (kg/m²), mean±SD	24.8±3.2	25.1±3.4	0.69
Graft type (BPTB/HT), n (%)	17/13 (56.7/43.3)	17/13 (56.7/43.3)	0.99
Injury to surgery (weeks), mean±SD	8.2±3.4	7.9±3.1	0.71
Meniscal injury, n (%)	12 (40.0)	14 (46.7)	0.61

Pre-injury Tegner score, mean±SD 7.2±0.9 7.4±0.8 0.35

TRG, traditional rehabilitation group; PRG, progressive rehabilitation group; BMI, body mass index; BPTB, bone-patellar tendon-bone; HT, hamstring tendon. Data presented as mean±standard deviation or number (percentage). p-values from independent t-tests or chi-square tests.

Primary Outcomes

Isokinetic Muscle Strength Recovery

Repeated measures ANOVA revealed significant group×time interactions for both quadriceps (F=18.42, p<0.001, partial η^2=0.301) and hamstring strength (F=21.38, p<0.001, partial η^2=0.337), indicating differential recovery trajectories between groups (**Table - 2**).

At 3 months, quadriceps LSI was significantly greater in PRG (72.4±7.8% vs 63.2±8.4%; p<0.001; Cohen's d=1.13). This advantage increased by 6 months (88.0±8.2% vs 75.0±9.1%; p<0.001; d=1.52) and persisted at 9 months (94.3±6.1% vs 85.7±7.8%; p<0.001; d=1.26). PRG achieved >90% LSI threshold at mean 6.8 months versus 8.7 months in TRG (p<0.001).

Similar patterns emerged for hamstring strength. At 6 months, PRG demonstrated 90.0±7.3% LSI compared to 78.0±8.5% in TRG (p<0.001; d=1.56). By 9 months, PRG maintained superior recovery (95.1±5.8% vs 87.2±7.1%; p<0.001; d=1.24). Angular velocity analysis showed consistent PRG advantages at both 60°/s and 180°/s testing speeds (all p<0.01).

Secondary Outcomes

Return to Sport

Kaplan-Meier survival analysis demonstrated significantly faster RTS in PRG. Mean time to RTS was 6.5±0.8 months (range 5.2-8.1) in PRG versus 9.2±1.1 months (range 7.8-11.3) in TRG (p<0.001). Cox proportional hazards regression yielded a hazard ratio of 3.42 (95% CI 2.18-5.37, p<0.001), indicating PRG participants were 3.4

times more likely to achieve RTS clearance at any given time point.

By 6 months, 63.3% (19/30) of PRG participants had achieved RTS compared to 10.0% (3/30) in TRG. By 9 months, RTS rates were 96.7% (29/30) for PRG and 76.7% (23/30) for TRG. All participants in PRG who achieved RTS maintained sport participation through study completion without functional limitations.

Graft Integrity and Complications

MRI assessment at 9 months revealed no between-group differences in graft integrity. All participants demonstrated intact grafts with appropriate signal intensity and positioning. Mean graft maturity scores (0-10 scale) were comparable: PRG 7.8±1.2 versus TRG 7.6±1.4 (p=0.58). No cases of graft failure, complete rupture, or >50% signal alteration occurred in either group.

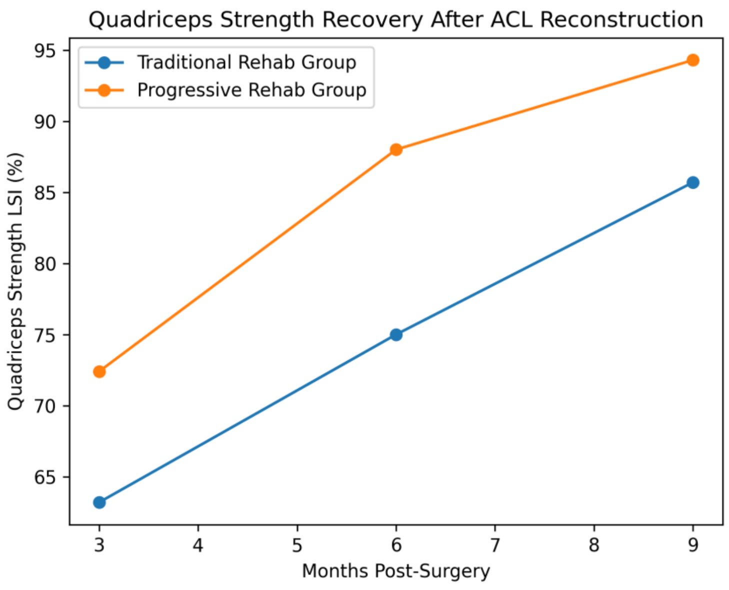
One participant in PRG sustained a contralateral ACL injury at 8.5 months (unrelated to study protocol, occurred during recreational skiing). No ipsilateral graft re-injuries occurred. One TRG participant developed arthrofibrosis requiring manipulation under anesthesia at 5 months. No infections, deep vein thromboses, or other serious adverse events occurred in either group. Overall complication rates did not differ significantly (PRG 3.3% vs TRG 3.3%; p=1.00). Quadriceps strength recovery (LSI %) between Progressive and Traditional Rehabilitation Groups is depicted in **Figure - 1**.

Table – 2: Primary Outcome Measures: Muscle Strength, ROM, Pain, and Functional Recovery.

Outcome Quadriceps LSI (%)	**Baseline**	**3 Months**	**6 Months**	**9 Months**	**p (int)** <0.001
TRG	48.2±9.3	63.2±8.4	75.0±9.1	85.7±7.8	
PRG	49.1±8.7	72.4±7.8***	88.0±8.2***	94.3±6.1***	
Hamstring LSI (%)					<0.001
TRG	52.3±8.9	67.5±7.8	78.0±8.5	87.2±7.1	
PRG	51.8±9.2	78.2±7.1***	90.0±7.3***	95.1±5.8***	
ROM Improvemen t (%)					0.002
TRG	62.4±11.2	74.8±9.3	85.0±7.8	94.2±5.4	
PRG	63.1±10.8	82.3±8.1**	92.0±6.4**	97.8±4.2*	
Pain VAS (0-10)					<0.001
TRG	5.8±1.4	4.9±1.2	4.5±1.3	2.8±1.1	
PRG	5.9±1.3	4.1±1.1*	3.2±1.1***	1.8±0.9***	
IKDC Score (0-100)					<0.001
TRG	48.3±9.8	62.4±8.7	72.8±9.2	80.0±6.8	
PRG	47.9±10.2	71.8±7.9***	84.2±6.5***	90.0±5.2***	

Data presented as mean±SD. LSI, limb symmetry index (percentage of contralateral limb strength); ROM, range of motion (percentage of pre-injury baseline); VAS, Visual Analog Scale; IKDC, International Knee Documentation Committee. p (int), p-value for group×time interaction from repeated measures ANOVA. Between-group comparisons at each time point: *p<0.05, **p<0.01, ***p<0.001 from post-hoc tests with Bonferroni correction.

Figure – 1: Quadriceps strength recovery (LSI %) between Progressive and Traditional Rehabilitation Groups.



Discussion

This randomized controlled trial provides Level I evidence supporting progressive rehabilitation following ACL reconstruction. Our findings demonstrate that PRG incorporating early neuromuscular training and functional exercises significantly accelerates strength recovery, improves functional outcomes, and expedites RTS without compromising graft integrity or increasing complication rates. These results challenge traditional paradigms emphasizing prolonged graft protection and suggest that appropriately progressed accelerated rehabilitation can safely optimize recovery trajectories.

Strength Recovery and Neuromuscular Function

The substantial strength advantages observed in PRG (>13% greater quadriceps LSI at 6 months; Cohen's d=1.52) represent clinically meaningful improvements. Quadriceps strength deficits are among the most persistent impairments following ACL reconstruction and strongly predict RTS success and re-injury risk [22, 23]. Early introduction of progressive resistance training and neuromuscular electrical stimulation in PRG likely prevented arthrogenic muscle inhibition and accelerated motor unit recruitment recovery. The large effect sizes (d=1.52-1.56 for primary strength outcomes) exceed minimal clinically important differences, supporting clinical relevance of our findings.

Functional Outcomes and Return to Sport

Superior IKDC scores in PRG (90.0 vs 80.0 at 9 months; p<0.001) reflect meaningful functional gains. IKDC scores >84 are associated with return to pre-injury activity levels [24]. The 2.7-month difference in RTS time represents substantial benefits for athletes, particularly in competitive contexts where prolonged absence jeopardizes career progression. Importantly, earlier RTS in PRG occurred without increased re-injury, suggesting readiness criteria were appropriately met. This challenges concerns that accelerated protocols promote premature RTS [25].

Graft Integrity and Safety Considerations

Perhaps most critically, our study demonstrates that progressive rehabilitation does not compromise graft integrity. MRI assessments confirmed comparable graft maturation, with no failures in either group. These findings align with biomechanical evidence that controlled loading promotes graft remodeling through mechanotransduction rather than compromising structural properties [13]. The similar complication rates (3.3% both groups) further support PRG safety. However, we emphasize that our protocol incorporated clear progression criteria and close supervision - indiscriminate "aggressive" rehabilitation without appropriate monitoring could increase injury risk.

Comparison with Existing Literature

Our findings extend previous research on accelerated ACL rehabilitation. Adams et al. (2012) reported similar RTS timelines with early aggressive rehabilitation but lacked comprehensive strength assessment [10]. Paterno et al. (2012) demonstrated improved neuromuscular outcomes with early training but noted higher re-injury rates during the first year post-RTS, contrasting with our findings [11]. This discrepancy may reflect our stringent RTS criteria requiring >90% LSI across multiple domains. Raines et al. (2017) meta-analysis concluded insufficient evidence existed for accelerated protocols, highlighting the value of our rigorously controlled trial design [16].

Clinical Implications

Our results support incorporating progressive rehabilitation principles into clinical practice, particularly for motivated athletes seeking expedited RTS. However, implementation requires careful patient selection, close monitoring, and objective progression criteria. Patients with concurrent meniscal repairs, revision procedures, or compliance concerns may require more conservative approaches. Clinicians should emphasize quality of movement over speed of progression, ensuring appropriate neuromuscular control before advancing to higher-demand activities. The three-times-weekly supervised therapy frequency in our protocol may not be universally feasible, potentially limiting generalizability.

Limitations

Several limitations warrant consideration. First, our single-center design with two surgeons may limit external validity, though standardized surgical techniques enhance internal validity. Second, 9-month follow-up precludes assessment of long-term outcomes, including late graft failures or post-traumatic osteoarthritis development. Third, participant and therapist blinding was impossible given intervention nature, potentially introducing performance bias, though blinded outcome assessment mitigates this concern. Fourth, our relatively young, athletic cohort (mean age 27 years, Tegner ≥6) may not generalize to older or less active populations. Fifth, the intensive supervision (three-times-weekly initially) may exceed resources available in many clinical settings. Finally, psychological readiness and kinesiophobia assessments, which influence RTS decision-making, were not comprehensively evaluated.

Future Directions

Future research should address several key areas. Long-term follow-up (2-5 years) is essential to assess graft durability, re-injury rates, and osteoarthritis development. Subgroup analyses based on patient characteristics (age, sex, graft type, sport type) could identify optimal candidates for progressive rehabilitation. Cost-effectiveness analyses comparing rehabilitation intensities would inform healthcare resource allocation. Investigation of minimum effective supervision frequency could enhance pragmatic applicability. Finally, biomechanical and neuromuscular outcome measures (e.g., landing mechanics, hip-knee-ankle kinematics, muscle activation patterns) would provide mechanistic insights into how progressive rehabilitation optimizes recovery.

Conclusion

This randomized controlled trial demonstrates that progressive rehabilitation incorporating early neuromuscular training and functional exercises significantly accelerates strength recovery (>13%

greater LSI at 6 months), improves patient-reported outcomes (10-point IKDC advantage), and expedites return to sport (2.7 months earlier) compared to traditional rehabilitation following ACL reconstruction. Critically, these benefits occurred without compromising graft integrity or increasing complication rates, supporting both efficacy and safety of accelerated protocols. These Level I findings provide robust evidence for progressive rehabilitation as the preferred approach for motivated athletes seeking optimal recovery, though successful implementation requires appropriate patient selection, close supervision, and adherence to objective progression criteria. Future research should examine long-term outcomes, identify patient-specific optimization strategies, and evaluate pragmatic implementation approaches to maximize the translational impact of these findings.

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