RESEARCH ARTICLE

The relationship between knee flexor and extensor strength, joint rotational stability, proprioception, and postoperative sports performance in patients following anterior cruciate ligament reconstruction

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Anterior cruciate ligament reconstruction (ACLR) is a widely performed surgical procedure aimed at restoring knee stability following anterior cruciate ligament (ACL) injuries. Recovery following ACLR is a dynamic and multifaceted process, which involves factors of muscle strength, proprioception, and joint stability. However, the temporal progression of these factors and their impact on sports performance have not yet been well understood. This study aimed to systematically assess functional recovery at various postoperative time points to investigate the relationship between muscle strength of the knee flexors and extensors, joint stability, proprioception, and sports performance. A retrospective analysis was conducted on 88 patients who had ACLR and were categorized into an early rehabilitation group (EG) and a late rehabilitation group (LG) to assess their knee joint stability, isokinetic muscle strength, proprioceptive function, and tactile sensitivity. The results showed that compared to the EG, the LG demonstrated significant improvements in KT-1000 arthrometer readings and pivot shift test outcomes, greater low-speed flexor strength, enhanced high-speed extensor strength, better joint position sense, and increased tactile sensitivity ($P < 0.05$). Furthermore, the LG showed significantly higher scores in sports performance assessments than EG ($P < 0.001$). In the early recovery, sports performance was primarily associated with extensor muscle strength and anterior knee stability, while, during the later phase, proprioceptive ability and balanced coordination between flexor and extensor muscle groups were more influential ($P < 0.01$). Functional recovery after ACLR followed distinct temporal patterns, and different physiological factors influenced sports performance at each stage of recovery. Rehabilitation strategies should therefore be tailored to the recovery timeline, emphasizing foundational strength and stability in the early phase, and progressing to neuromuscular control and proprioceptive training in the later phase.

Keywords: anterior cruciate ligament reconstruction; knee functional recovery; isokinetic strength test; proprioception; sports performance.

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Introduction

Anterior cruciate ligament (ACL) injuries are among the most common knee injuries in sports medicine, and ACL reconstruction (ACLR) is considered as the gold standard for restoring knee stability and function [1]. Despite advances in surgical techniques, the recovery of full sports function remains challenging. Research indicated that approximately 20 - 30% of patients fail to return to their pre-injury level of athletic performance after ACLR, and the risk of re-injury remains high [2, 3]. These findings highlight the limitation of anatomical reconstruction alone in achieving complete functional recovery. Notably, key factors such as knee muscle strength, joint stability, and proprioception are crucial for rehabilitation success [4]. However, these factors interact in a complex manner, influencing sports performance in distinct yet interdependent manners. A more comprehensive understanding of these interrelations is necessary to refine rehabilitation strategies and improve outcomes for ACLR patients.

In recent years, the importance of muscle strength, joint stability, and proprioception in ACLR rehabilitation has been recognized, while the interaction among these elements was not fully understood. One of the most prominent impairments observed post-ACLR is the imbalance between knee flexor and extensor muscle strength [5-7]. Weaknesses in the quadriceps and hamstrings negatively impact the lower limb kinetic chain, leading to reduced athletic performance such as lower jump height and slower change-of-direction speed. Similarly, deficits in joint rotational stability, a critical component of dynamic control, place patients at the increased risk of knee instability during high-velocity movements [8]. Moreover, proprioceptive dysfunction impedes neuromuscular control, resulting in delayed postural responses and poor coordination during complex athletic tasks. These three factors including muscle strength, joint stability, and proprioception are closely interrelated, and their combined effects play a fundamental role in functional recovery [9, 10]. Therefore, addressing each factor in isolation may not lead to significant improvements in overall sports performance.

Although previous research has examined the individual roles of muscle strength, joint stability, and proprioception in ACLR recovery, the combined effects of these factors and their evolution over time remain poorly understood. Additionally, the existing studies mainly rely on cross-sectional designs, limiting the ability to draw causal links between functional parameters and sports performance. To address these gaps, this study employed a longitudinal design to track the progression of flexor and extensor muscle strength, joint rotational stability, and proprioceptive function at multiple stages of recovery post-ACLR to clarify how these factors influenced performance in various sport-specific movements such as linear running, directional changes, and jumping. The results provided a theoretical basis for developing targeted rehabilitation protocols, ultimately enhancing clinical outcomes and optimizing functional recovery in ACLR patients.

Materials and methods

Selection and grouping of research subjects

A total of 52 males and 36 females, aged from 18 to 45 years old were involved in this study. All patients were recruited from the specialized rehabilitation and sports medicine clinic affiliated with Fujian Sports Vocational Education and Technology College (Fuzhou, Fujian, China) between May 2022 and May 2025. Inclusion criteria were patients with a unilateral complete ACL rupture, confirmed by MRI and clinical evaluation, surgical intervention performed by the same experienced orthopedic team, adherence to a standardized postoperative rehabilitation program, and availability of follow-up data including at least 12 months of postoperative records. Exclusion criteria included meniscal injuries requiring surgical resection, existing knee osteoarthritis, neurological disorders or peripheral nerve injuries, and serious postoperative complications such as graft rupture or infection. Thirty-eight (38) patients were defined as the early group (EG) and were evaluated 12 – 18 months after surgery, while 50 patients were defined as the late group (LG) and were evaluated more than 18 months after surgery. All procedures of this study were approved by the Ethics Committee of Fujian Sports Vocational Education and Technology College (Approval No. 24-361).

Clinical data collection

Demographic and clinical data including age, sex, body mass index (BMI), age at the time of surgery, surgical side, time interval from injury to surgery, and average duration of follow-up were obtained from the electronic medical record system.

Knee stability assessment

Anterior tibial translation was measured bilaterally using Medmetric KT-1000/2000 arthrometer (Medmetric Corporation, San Diego, CA, USA) by applying a standardized anterior force of 134N at 30° knee flexion. The side-to-side difference (in millimeters) was recorded with a difference larger than 3 mm as the indicative of clinical instability. Manual assessments including the Lachman test being graded based on tibial displacement of 1 - 5 mm (Grade I), 6 – 10 mm (Grade II), > 10 mm (Grade III) and the pivot shift test with no displacement (Grade 0), gliding (Grade 1), subluxation (Grade 2), momentary locking (Grade 3) conducted independently by two experienced orthopedic surgeons. Any discrepancies were resolved through a third examiner's evaluation.

Isokinetic muscle strength testing

Strength of the knee flexor and extensor muscles was evaluated using the Biodex System 4 Pro isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA). Testing speeds were set at 60°/s for maximal strength and 180°/s for endurance assessment. Patients were seated with their hips flexed to 85°, and the dynamometer's arm was aligned with the lateral femoral epicondyle. The test included five warm-up repetitions, three maximal voluntary contractions with 90-second rest intervals, then five formal repetitions of flexion and extension. Peak torque (Nm) was normalized to body weight (PT/BW), and the limb symmetry index (LSI) was calculated as the ratio of the involved side to the uninvolved side.

Proprioception ability testing

Proprioceptive ability was assessed using active joint position reproduction (AJPR) and threshold to detect passive motion (TTDPM) methods. AJPR was conducted using an ISOMOVE electronic goniometer (ISOMOVE GmbH, Furtwangen, Germany). The patient's knee was passively positioned at 30° flexion and held for 10 seconds without visual cues. The patient was then asked to reproduce the position actively. The mean absolute error in degrees from three attempts was recorded. TTDPM was performed by passively flexing knee at a rate of 0.5°/s. The patient was instructed to press a button upon first detecting movement. The angular difference between the actual and perceived movement onset was measured in flexion and extension directions with the average of three trials as the final value.

Plantar tactile sensitivity testing

Semmes-Weinstein monofilament test was employed with sensory thresholds being assessed at three plantar sites including the first metatarsal head, fifth metatarsal head, and central heel while the patient was in a supine position and closed eyes. Monofilaments (North Coast Medical, Inc., Morgan Hill, CA, USA) of varying diameters with 0.008 – 300 g of pressure were applied perpendicularly for 1 – 1.5 seconds. The minimum detectable pressure (g) was recorded at each site with three trials per site and the lowest value as the final result. In addition, vibration perception threshold was determined by applying a 100 Hz vibratory stimulus using Vibrometer (Vibration Research Inc., Lehi, UT, USA) to the area below the medial malleolus. While the vibration amplitude gradually increased, the threshold (μm) at which the patient first perceived the vibration was recorded.

Sports function evaluation

The Tegner activity scale was used to assess sports performance, ranging from 0 to 10, with higher scores reflecting greater athletic capability. Patients' best preoperative and postoperative activity levels were recorded *via* a standardized questionnaire administered by rehabilitation physicians. The International Knee Documentation Committee (IKDC) knee scores

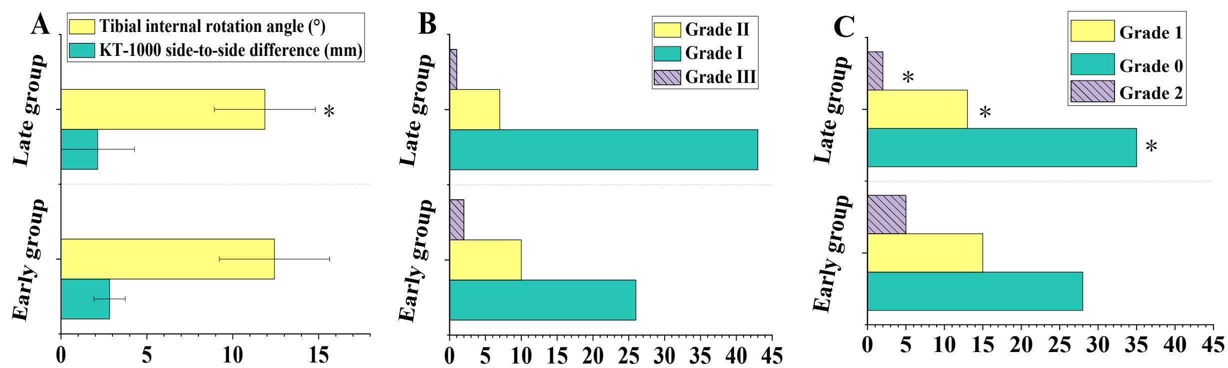

Figure 1. Comparison of knee stability in subjects. **A.** KT-1000 difference (mm) and tibial internal rotation angle (°). **B.** Lachman test. **C.** Pivot shift test. *: *P* < 0.05.

ranged from 0 to 100 was applied to assess symptoms, sports activity, and daily functional ability across 10 items with higher scores indicating better knee function. The Lysholm knee scoring scale was also used to evaluate knee function based on eight parameters including limping, need for support, and joint locking. Scores range from 0 to 100 with scores above 84 indicating good knee function.

Quality control

To guarantee data consistency and reliability, all assessments including knee stability tests, isokinetic strength measurements, proprioception evaluations, and plantar tactile sensitivity tests were conducted following a uniform protocol by two dedicated, experienced rehabilitation therapists to standardize the procedures. Testing was performed in a controlled environment that was maintained at 24 ± 1°C. Before assessments, patients completed a standardized 15-minute warm-up to reduce the influence of external variables.

Statistical analysis

SPSS 26.0 (IBM, Armonk, NY, USA) was employed for statistical analysis. Continuous variables were assessed for normality using the Shapiro-Wilk test. Variables following a normal distribution were reported as mean ± standard deviation ($\bar{x}$ ± s). Group comparisons were conducted using paired t-tests. Variables that did not meet normality assumptions were expressed as median with interquartile range [M (Q1 – Q3)] and analyzed using the Wilcoxon signed-rank test. Partial correlation analysis was employed to examine associations between variables while adjusting for confounding factors such as age, height, and weight. Categorical variables were compared using the Chi-square (χ^2) test or the Fisher's exact test where appropriate. Statistical significance was defined as P value less than 0.05.

Results

Comparison of EG and LG

The comparison of baseline characteristics, knee stability, isokinetic strength, sensory function, and sports performance between the EG and LG revealed several key differences and similarities. There were no significant differences between the EG and LG in demographic variables including age, gender, BMI, the time from injury to surgery, and the side of surgery.

(1) Knee stability test

results showed significantly improved knee stability in the LG compared to the EG (*P* < 0.01). However, no significant difference was found in the tibial internal rotation angle between the groups. In graded assessments, the Lachman test scores showed no significant difference, while the pivot shift test revealed marked improvement in stability for the LG (*P* < 0.05) (Figure 1).

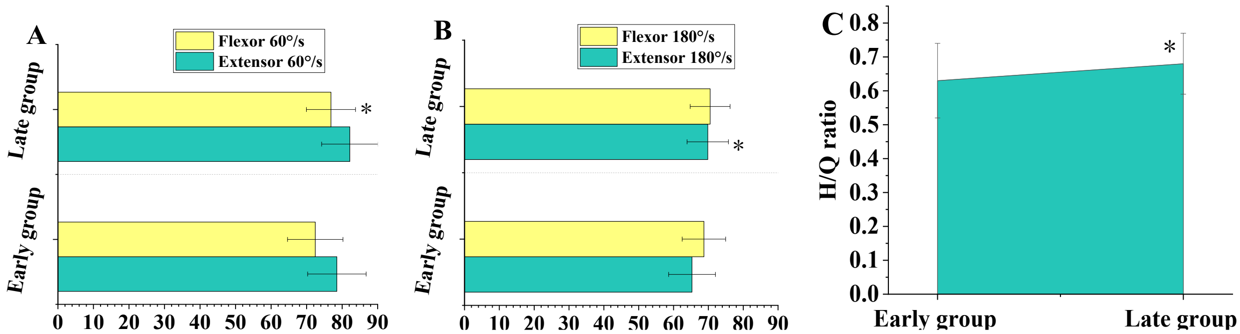

Figure 2. Comparison of isokinetic strength test results in subjects. **A.** extensors at 60°/s and flexors at 60°/s. **B.** extensors at 180°/s and flexors at 180°/s. **C.** H/Q ratio. *: $P < 0.05$.

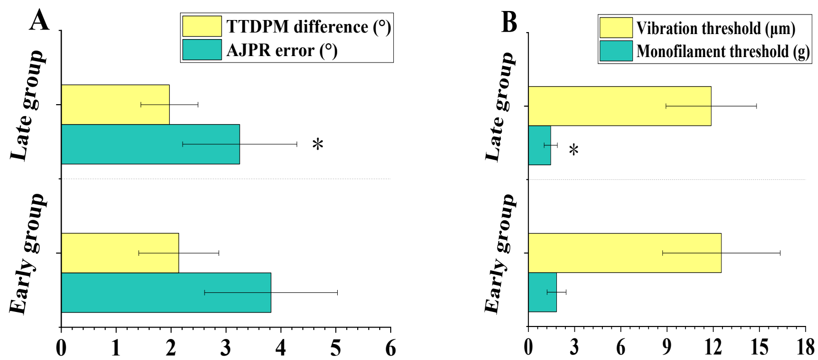

Figure 3. Comparison of sensory function test results in subjects. **A.** AJPR error (°) and TTDPM difference (°). **B.** monofilament tactile threshold (g) and vibration perception threshold (μm). *: $P < 0.05$.

(2) Isokinetic strength test

The results demonstrated significant differences in muscle strength recovery between the groups with flexor muscle strength at 60°/s and extensor strength at 180°/s significantly greater in the LG than EG, respectively ($P < 0.05$). Although differences in extensor strength at 60°/s and flexor strength at 180°/s did not show statistical significance, both did demonstrate trends toward higher values in the LG than EG. The hamstring-to-quadriceps (H/Q) ratio was significantly higher in the LG ($P < 0.05$), supporting the observation that the LG had better muscle strength balance. The limb symmetry index (LSI) analysis confirmed that the LG's muscle strength recovery was closer to the healthy side across all measures (Figure 2).

(3) Sensory function and proprioception ability tests

The results of sensory function test showed that the LG outperformed the EG in several sensory function measures. The AJPR error was significantly lower in the LG than EG ($P < 0.05$), and the monofilament tactile threshold showed significant improvement ($P < 0.01$). However, no statistically significant differences were observed for the TTDPM and vibration perception threshold (Figure 3).

(4) Sports function evaluation

The sports function scores showed that the LG exhibited notably higher scores than that of EG in three indicators including Tegner score (6.8 ± 1.3 *vs*. 5.2 ± 1.1), IKDC subjective score (82.6 ± 10.3 *vs*. 68.4 ± 12.7), and Lysholm score (88.3 ± 7.6 *vs*. 78.5 ± 9.2) ($P < 0.01$) (Figure 4).

Correlation analysis between functional indicators and sports performance

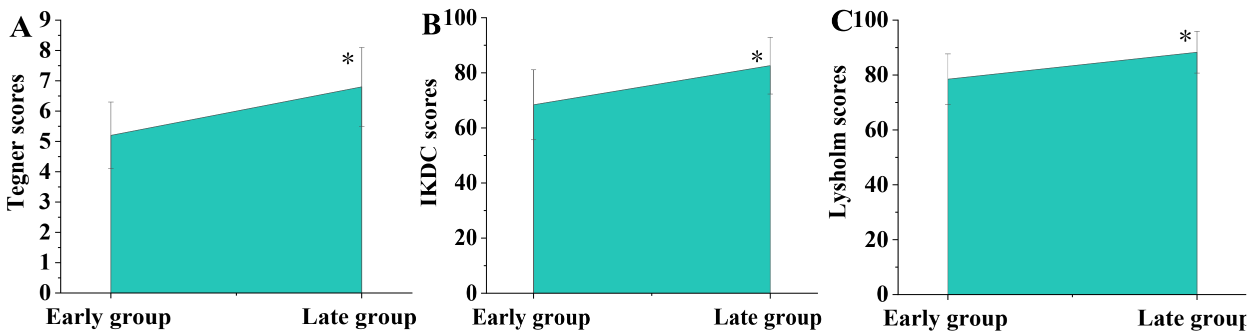

Figure 4. Comparison of sports function scores in subjects. **A.** Tegner score. **B.** IKDC subjective score. **C.** Lysholm score. *: $P < 0.05$.

The results showed that, in the EG, the KT-1000 difference demonstrated a significant negative correlation among all three sports function scores with Tegner score (r = -0.42, *P* = 0.011), IKDC score (r = -0.38, *P* = 0.021), and Lysholm score (r = -0.35, *P* = 0.032), respectively. Extensor muscle strength at 60°/s demonstrated a significant positive correlation with all three scores (r = 0.43 - 0.51, *P* < 0.01). Flexor muscle strength at 60°/s was significantly correlated with the Tegner score (r = 0.39, *P* = 0.018) and IKDC score (r = 0.36, *P* = 0.028). The active joint position reproduction (AJPR) error was significantly negatively correlated with the Tegner score (r = -0.35, *P* = 0.033) only. The monofilament tactile threshold did not show a significant correlation with any of the sports function scores. In the LG, the KT-1000 difference remained significantly negatively correlated with all three sports function scores with Tegner score (r = -0.38, *P* = 0.007), IKDC score (r = -0.35, *P* = 0.015), and Lysholm score (r = -0.33, *P* = 0.021), respectively. Extensor muscle strength at 60°/s exhibited a strong positive correlation with all three scores (r = 0.41 - 0.46, *P* < 0.01), while flexor muscle strength at the same speed also showed significant correlations with all scores (r = 0.38 - 0.44, *P* < 0.01). The AJPR error was significantly negatively correlated with all sports function scores (r = -0.35 to -0.41, *P* < 0.05). Additionally, the monofilament tactile threshold showed significant negative correlations with the Tegner score (r = -0.33, *P* = 0.019) and the IKDC score (r = -0.30, *P* = 0.034).

Discussion

The ACLR remains the gold standard for treating ACL ruptures with postoperative functional recovery being a key focus in clinical practice [11]. Despite advancements in surgical techniques, patients still exhibit significant differences in postoperative motor performance, influenced by factors such as knee joint stability, muscle strength recovery, and proprioception [12]. This study systematically assessed functional recovery at various postoperative stages by exploring the relationships among knee flexor and extensor muscle strength, joint stability, proprioception, and sports performance, offering valuable insights for enhancing rehabilitation protocols. The results indicated that, with increasing postoperative time, knee function indicators demonstrated distinct stage-specific improvements, and the predictive relevance of different functional measures for sports performance evolved, which held significant implications for clinical rehabilitation strategies. Regarding knee stability recovery, the LG showed significantly better outcomes than the EG in both objective measures of KT-1000 arthrometer readings and clinical pivot shift test, aligning with the biological process of graft ligamentization. Although no statistically significant difference was observed in Lachman test grading, the LG showed a reduced positive rate, suggesting that clinical physical exams might have limited sensitivity to subtle changes in stability [13, 14]. Compared to previous reports, the KT-1000 difference observed in the LG in this study was closer to that of the healthy side, reflecting that all patients underwent a standardized rehabilitation program, underscoring the critical role of systematic rehabilitation. However, no significant difference was found between the groups in tibial internal rotation angle, suggesting that recovery of rotational stability might require a longer duration or more specialized training approaches. This insight held important implications for designing clinical rehabilitation protocols [15]. Further, this study revealed several key observations based on isokinetic testing regarding muscle strength recovery, which displayed velocity-specific characteristics. Extensor muscles demonstrated significant improvement at higher speeds, while flexor muscles demonstrated significant gains at lower speeds. This pattern reflected differences in muscle fiber recruitment depending on contraction velocity. In addition, the hamstring-to-quadriceps (H/Q) strength ratio as an indicator of muscle balance was significantly increased in the LG. Although it had not reached the optimal threshold, this improvement suggested gradually optimizing neuromuscular control [16]. The LSI also showed a positive trend in the LG with extensor LSI values remaining below the 90% clinical benchmark, which indicated that quadriceps inhibition might persist beyond 18 months post-surgery, providing valuable insight for defining rehabilitation endpoints. Sensory function assessments revealed differential recovery patterns among various modalities. The AJPR test showed significant improvement in the LG, whereas no significant differences were observed in TTDPM. This divergence reflected that these tests evaluated distinct physiological mechanisms [17, 18]. Similarly, tactile function recovery was characterized by marked improvement in monofilament thresholds but minimal change in vibration perception thresholds. These results highlighted the need for tailored sensory rehabilitation strategies that addressed the specific characteristics of each modality. Moreover, the relationship between sensory function and sports performance had evolved. In the LG, active proprioception and tactile sensitivity demonstrated stronger predictive value for sports outcomes, suggesting an increasing importance of advanced neuromuscular control as fundamental motor functions recover [19]. Regarding sports function scores, the Tegner activity scale, IKDC subjective score, and Lysholm score were significantly higher in the LG than in the EG, reflecting progressive improvements in overall functional status with longer postoperative duration. Importantly, correlation analyses revealed dynamic shifts in predictors of sports performance throughout recovery. In the early phase, extensor strength and knee stability were the most influential factors, whereas in the later phase, proprioception and flexor strength emerged as stronger predictors. This shift highlighted the importance of adjusting rehabilitation priorities over time, initially focusing on restoring muscle strength and stability, and then gradually strengthening neuromuscular control and motor coordination [20].

The findings of this study provided several valuable recommendations for clinical rehabilitation practice. Rrehabilitation plan should be developed in stages according to the postoperative time with the focus on restoring basic muscle strength and stability. In the middle stage, targeted muscle strength balance training should be carried out, and in the later stage, the focus should be on higher neuromuscular control. Further, functional evaluations should employ a multidimensional approach, incorporating objective measures of stability, isokinetic muscle strength testing, and proprioceptive assessments to capture the patient's recovery status comprehensively. Patients demonstrating significant functional impairments beyond 18 months post-surgery might benefit from more specialized, targeted interventions. The results advocated for developing evidence-based rehabilitation endpoint criteria rather than relying solely on postoperative time to guide clinical decision-making. This study had some limitations. As a retrospective analysis, despite rigorous quality control, it could not fully account for all potential confounding variables. Furthermore, muscle strength at higher contraction speeds was neither assessed nor radiologically evaluated for graft integration. These aspects represented opportunities for refinement in future research. It was recommended that subsequent studies should incorporate longer follow-up durations and combine advanced imaging and electrophysiological techniques to investigate the biological mechanisms underpinning functional recovery more thoroughly.

Conclusion

This study confirmed that knee function recovery following ACLR exhibited distinct temporal patterns. Patients after 18 months post-surgery exhibited significantly greater knee stability, improved muscle strength recovery, and enhanced proprioception compared with those in the 12 to 18-month postoperative range. Notably, there were significant improvements in high-speed extensor strength and low-speed flexor strength. Correlation analysis revealed that, during the early recovery phase of 12 to 18 months, sports performance was primarily influenced by extensor muscle strength and anterior stability. In contrast, in the later phase of more than 18 months, proprioception and the coordinated function of flexor and extensor muscles became more prominent. The recovery of rotational stability and vibration perception was slower, highlighting the need for targeted rehabilitation strategies. These findings provided crucial insights for developing stage-specific rehabilitation programs post-ACLR, emphasizing the importance of tailoring rehabilitation priorities to the evolving stages of recovery. Early rehabilitation should focus on restoring foundational muscle strength and stability, while later stages should prioritize enhancing neuromuscular control to optimize functional outcomes. The results further advocated for personalized rehabilitation plans based on comprehensive functional assessments, rather than relying solely on postoperative time as the benchmark for recovery.

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