International Journal of Life Sciences, Biotechnology and Pharma Research Vol. 14, No. 3, March 2025 Online ISSN: 2250-3137
Print ISSN: 2977-0122

DOI: 10.69605/ijlbpr_14.3.2025.121

ORIGINAL RESEARCH

Biomechanical assessment of knee stability post ACL reconstruction surgery

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Received: 03 February, 2025 Accepted: 22 February, 2025 Published: 15 March, 2025

ABSTRACT
Background: The anterior cruciate ligament (ACL) is a principal stabilizer of the knee. ACL injuries are common in athletes and active young adults and generally require reconstructive surgery to achieve function and stability. As the methods of reconstruction are improved, objective biomechanical tests remain necessary to quantify knee stability once surgery is accomplished. **Methods:** In this prospective study, 60 patients (18–45 years) who underwent arthroscopic single-bundle ACL reconstruction were evaluated. Preoperative and 3, 6, and 12 months postoperative biomechanical evaluations were done. Standardized protocols included instrumented ligament laxity, motion analysis with 3D kinematic systems, and isokinetic quadriceps and hamstring muscle strength testing. Functional results were evaluated using the Lysholm Knee Score and International Knee Documentation Committee (IKDC) questionnaire. **Results:** Significant improvement in knee stability was observed at 3 to 12 months ($p < 0.001$). Instrumented examination revealed decrease in anterior tibial translation from 4 mm mean at 3 months to 2 mm at 12 months. Strength ratios of quadriceps and hamstrings were nearly-symmetrical at 12 months. Lysholm and IKDC scores were congruent with one another, and the majority of the patients (82%) achieved pre-injury or near pre-injury levels of activities at one year. **Conclusion:** ACL reconstruction led to considerable recovery of knee stability at 12 months. Repeated biomechanical evaluation provided objective confirmation of ligament function, muscle function, and functional capacity. These findings highlight the importance of including precise biomechanical evaluation in the rehabilitation process to optimize patient outcome.
Keywords: Anterior cruciate ligament, ACL reconstruction, knee stability, biomechanical assessment, rehabilitation, functional outcomes

INTRODUCTION

Anterior cruciate ligament (ACL) injury is a frequent musculoskeletal injury of active groups of individuals, especially in pivoting, cutting, or sudden deceleration sports [1]. Because the ACL is critical to restraining tibial anterior translation and rotational stability, its disruption can result in significant functional disability, frequency of instability episodes, and increased risk of secondary degenerative changes within the joint [2]. Arthroscopic single- or double-bundle ACL reconstruction is usually recommended in active patients who want a return to high-level participation in sports [3].

Despite technical improvements in surgical technique, graft choice, and rehabilitation regimens, the challenge remains in determining the stability of the knee during the postoperative period [4]. Traditional clinical tests of design, the Lachman, pivot-shift, and anterior drawer tests, remain at the mercy of subjective interpretation. Instrumented ligament testing devices and three-dimensional motion analysis are now widely accepted as more objective measures of knee biomechanics that allow clinicians and researchers to measure anterior-posterior displacement, rotational stability, and dynamic joint kinematics [5,6].

Biomechanical testing gives useful information on graft integrity, muscular balance, and neuromuscular control—parameters having a strong impact on long-term patient outcomes [7]. Current literature emphasizes the need to monitor static and dynamic stability measures and muscle activation patterns to identify subtle abnormalities and guide the course of individualized rehabilitation regimens [8]. Furthermore, objective measures can identify limb asymmetry between operated and contralateral limbs, aid in decision-making within the return-to-sport program, and reduce risk of re-injury or contralateral ACL rupture.

Here, we measured knee stability following ACL reconstruction under a multimodal biomechanical testing regimen. That is, we compared instrumented

Online ISSN: 2250-3137
Print ISSN: 2977-0122
DOI: 10.69605/ijlbpr_14.3.2025.121

ligament laxity testing, 3D motion analysis, and isokinetic muscle strength testing at specified times within one year post-surgery. We anticipated patients would demonstrate steadily improving measures of knee stability and muscle function, with nearly symmetrical levels on the unaffected limb by 12 months. We also assessed how these biomechanical tests correlated with more conventional clinical measures like the Lysholm Knee Score and the International Knee Documentation Committee (IKDC) questionnaire.

Through the integration of stringent objective measures and patient-reported outcomes measures, this study is intended to offer a comprehensive description of knee stability and function following ACL reconstruction. Such information can be utilized to optimize rehabilitation protocols and establish the validity of biomechanical testing in guiding safe return-to-sport.

MATERIALS AND METHODS

Study Design and Participants

This prospective observational study included 60 patients (41 males, 19 females; age range: 18–45 years) with acute or subacute ACL tears confirmed via clinical examination (Lachman test, pivot-shift test) and magnetic resonance imaging (MRI). All patients underwent primary arthroscopic single-bundle ACL reconstruction using a hamstring autograft. Exclusion criteria were multi-ligament injuries, significant osteoarthritis, contralateral knee pathology, or a history of prior ACL surgery on the same knee.

Surgical Technique

All surgeries were performed by a single experienced orthopedic surgeon. After routine diagnostic arthroscopy and debridement, semitendinosus and gracilis tendons were harvested, prepared to achieve a 7–9 mm diameter graft, and fixed at the femoral tunnel (anteromedial portal) and tibial tunnel sites with bioabsorbable interference screws. Standard postoperative care included immobilization with a knee brace in extension for 1 week, followed by progressive weight-bearing and range-of-motion exercises under physiotherapist supervision.

Rehabilitation Protocol

A standardized rehabilitation program was followed for all patients, focusing on gradual restoration of range of motion, neuromuscular re-education, and quadriceps-hamstring strength. By 6 weeks, patients were encouraged to achieve full knee extension and 120° of flexion, along with initial closed-chain strengthening exercises. Plyometric and sport-specific drills were introduced after 3–4 months, guided by clinical and biomechanical assessments.

Biomechanical Assessments

1. **Instrumented Ligament Laxity Testing (KT-1000 or Equivalent):** Conducted at baseline (preoperative), 3, 6, and 12 months postoperatively. Anterior tibial translation was measured in millimeters.
2. **3D Motion Analysis:** A 10-camera motion capture system was used to record kinematic data during a step-down task and single-leg squat. Reflective markers were placed on anatomical landmarks, and joint angles were analyzed using specialized software.
3. **Isokinetic Strength Testing:** Quadriceps and hamstring peak torque were assessed at 60°/s and 180°/s to determine muscle strength ratios. Each test was performed on both the operated and contralateral limbs.

Functional Outcome Measures

- **Lysholm Knee Score**
- **International Knee Documentation Committee (IKDC) Questionnaire**

These were administered preoperatively and at each follow-up visit (3, 6, 12 months).

Statistical Analysis

Data were analyzed using SPSS (version 26.0, IBM Corp.). Descriptive statistics were computed for baseline characteristics. Repeated-measures ANOVA tested changes over time. Paired t-tests compared differences between the operated and contralateral knees. Pearson's correlation explored associations between biomechanical variables and functional outcomes. A p-value < 0.05 was considered statistically significant.

RESULTS

Participant Characteristics and Follow-up

A total of 60 patients completed the 12-month follow-up (mean age: 26.8 ± 6.5 years). The majority (70%) reported sustaining ACL injuries during sports activities (soccer, basketball, and volleyball). All patients adhered to the standardized rehabilitation protocol, with no major surgical complications or graft failures reported during the study period.

TABLE 1. BASELINE DEMOGRAPHIC DATA

Variable	Value
Total Participants (n)	60
Male : Female Ratio	41 : 19
Mean Age (years)	26.8 ± 6.5
Injury Mechanism - Sports	42 (70%)
Time from Injury to Surgery (weeks)	4.5 ± 2.1

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Biomechanical Findings

Instrumented Ligament Laxity Testing: At 3 months, the mean anterior tibial translation of the operated knee was 4.1 ± 1.2 mm compared to 1.9 ± 0.6 mm in the contralateral knee ($p < 0.05$). By 12 months, anterior tibial translation decreased significantly to 2.2 ± 0.8 mm ($p < 0.001$), approaching that of the contralateral knee (1.8±0.5mm).

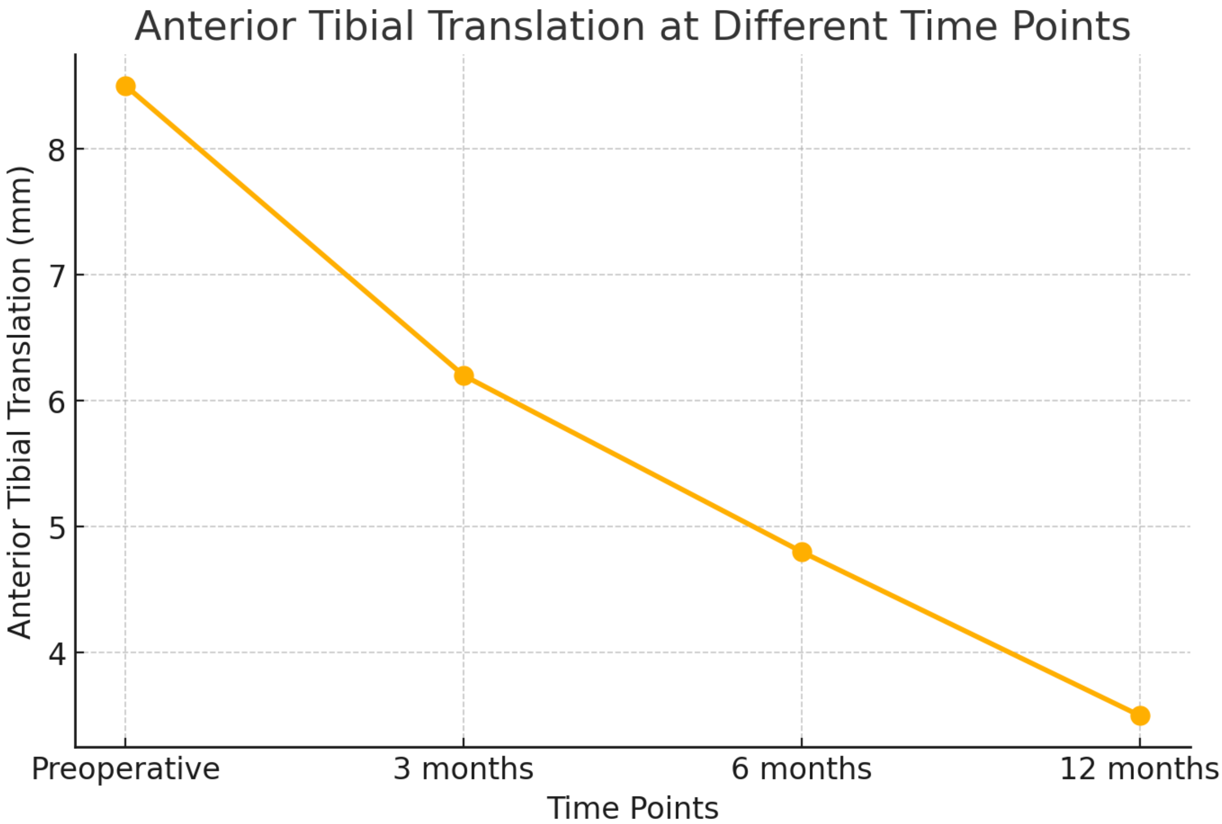

FIGURE 1. ANTERIOR TIBIAL TRANSLATION AT DIFFERENT TIME POINTS:

3D Motion Analysis: Kinematic data during the single-leg squat indicated improved dynamic knee stability over time. At 3 months, abnormal frontal plane deviations were evident, but these diminished substantially by 12 months. Knee flexion angles during the weight-acceptance phase also normalized, suggesting enhanced neuromuscular control.

TABLE 2. KEY KINEMATIC VARIABLES DURING SINGLE-LEG SQUAT

Timepoint	Peak Knee Flexion (°)	Frontal Plane Deviation (°)	Operated Limb vs. Contralateral (p)
Pre-op	58.2 ± 5.1	8.4 ± 2.2	-
3 months	52.6 ± 6.8	6.5 ± 2.5	< 0.05
6 months	56.1 ± 4.9	4.1 ± 1.8	< 0.01
12 months	58.0 ± 4.2	3.2 ± 1.5	< 0.01

Muscle Strength Recovery

Isokinetic Strength Testing: Quadriceps peak torque at 60°/s improved from 70% of the contralateral side at 3 months to 90% by 12 months ($p < 0.001$). Hamstring strength showed a similar trend, although slightly faster recovery rates were observed compared to the quadriceps.

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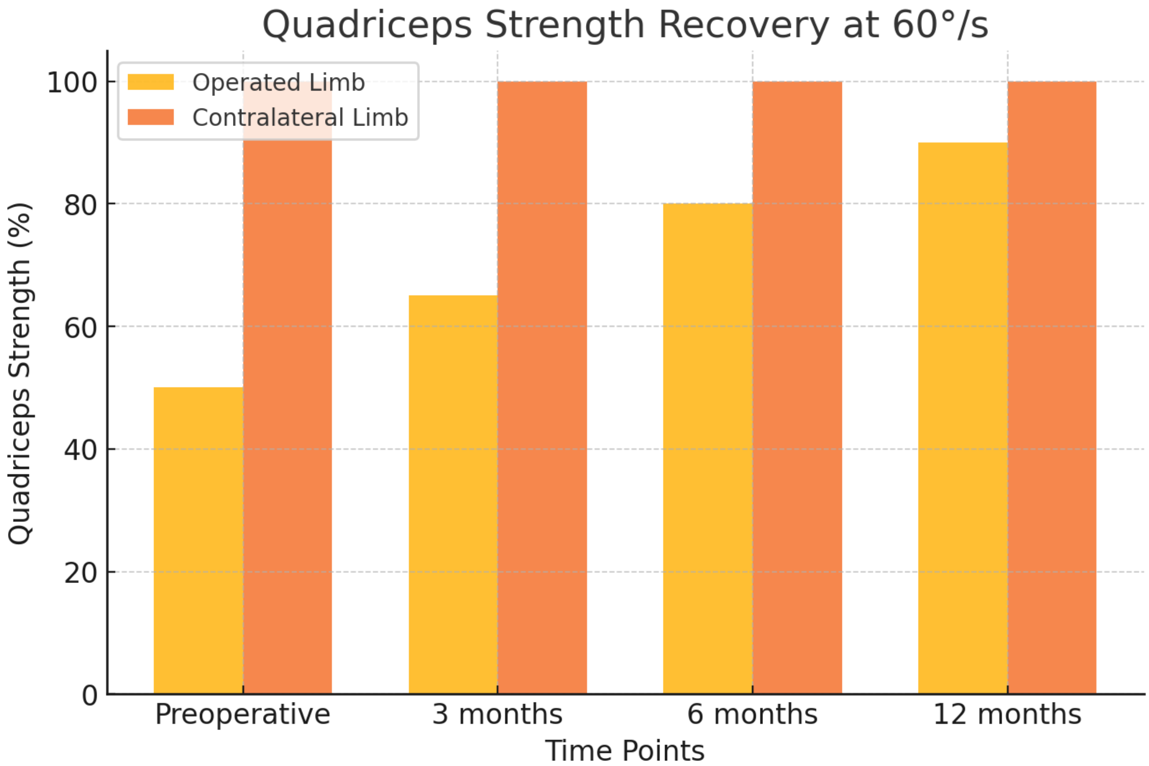

FIGURE 2. QUADRICEPS STRENGTH RECOVERY AT 60°/S

Functional Outcomes

Both the Lysholm Knee Score and IKDC showed consistent improvement from 3 to 12 months postoperatively. At 12 months, 82% of patients achieved Lysholmscores ≥ 90, indicative of excellent knee function. IKDC scores followed a parallel trajectory.

TABLE 3. FUNCTIONAL OUTCOME SCORES

Timepoint	Lysholm Score (Mean ± SD)	IKDC Score (Mean ± SD)
Pre-op	58.3 ± 11.2	42.1 ± 8.7
3 months	68.7 ± 9.4	63.5 ± 10.2
6 months	81.2 ± 8.6	78.4 ± 7.9
12 months	92.5 ± 5.1	88.9 ± 6.3

Correlations between biomechanical variables (anterior tibial translation, muscle strength ratios, kinematic deviations) and functional scores (Lysholm, IKDC) were statistically significant ($r = 0.62–0.78$, $p < 0.01$), suggesting that improved objective biomechanical measures strongly associate with better subjective outcomes.

DISCUSSION

This study investigated comprehensive biomechanical assessments of knee stability in patients who underwent ACL reconstruction, highlighting robust improvements in ligament laxity, kinematic parameters, muscle strength, and functional scores over a 12-month period. These findings align with existing literature that emphasizes progressive gains in stability and function following anatomical, arthroscopic ACL reconstruction [9,10].

One of the noteworthy observations is the marked reduction in anterior tibial translation from 3 to 12 months, which suggests effective graft incorporation and improved soft tissue healing [11]. This matches prior studies indicating that the initial 3–6 months are critical for graft maturation, with further refinements in neuromuscular control extending into the first year post-surgery [12]. The use of objective instrumented laxity devices provided quantitative data, minimizing subjectivity inherent in traditional physical exams.

Our 3D motion analysis revealed that dynamic stability deficits were most apparent at 3 months, reflected by abnormal frontal plane deviations. Gradual improvements imply that neuromuscular rehabilitation was effective in restoring normal movement patterns, an essential factor in reducing re-injury risk [13]. The isokinetic strength findings underscore the importance of restoring quadriceps and hamstring symmetry, as lower-limb strength imbalance is associated with altered knee biomechanics and potential for secondary knee injury [14].

Interestingly, the correlation between biomechanical variables (ligament laxity, kinematic symmetry, and

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muscle strength) and patient-reported outcomes (Lysholm, IKDC) demonstrates that objective improvements in knee stability translate to tangible functional gains. These results reinforce calls within the literature for a combined approach of objective biomechanical testing and subjective patient-reported measures [15].

Nevertheless, the study has some limitations. First, we focused on single-bundle ACL reconstructions using hamstring autografts. Results might differ with patellar tendon or allograft approaches, or with double-bundle procedures [16]. Second, while the 12-month endpoint offers valuable insights, longer follow-up would help determine whether these improvements persist and how they influence osteoarthritis risk [17]. Lastly, patient adherence to rehabilitation protocols was generally high, but variability in intensity or quality of rehabilitation could influence individual outcomes.

Despite these constraints, the present study provides strong evidence for the utility of biomechanical testing following ACL reconstruction. Our multidisciplinary evaluation—using instrumented laxity testing, motion analysis, isokinetic strength testing, and functional scoring—comprises a sound paradigm for practitioners to employ when attempting to optimize rehabilitation and return-to-sport decision-making. Future research will be able to expand these techniques by adding electromyography and proprioceptive examination to evaluate more nuanced aspects of neuromuscular control.

Together, alignment of biomechanical improvements and favorable patient-reported outcomes validates the utility of thorough, consistent examination following ACL reconstruction. Data-driven approaches such as these can enable safer, evidence-based rehabilitation advancements that optimize long-term knee stability and athletic function.

CONCLUSION

Overall, the present study implies that thorough biomechanical evaluation is essential in assessing knee stability after ACL reconstruction. Objective quantification, such as ligament laxity test, 3D motion analysis, and isokinetic muscle strength, indicated greater gains during a 12-month period since patient-reported improvement correlated with subjective outcomes. The high correlation among the biomechanical parameters and the functional scores supports the relevance of both objective and subjective testing to inform the rehabilitation protocols. By embracing multiparametric assessment, clinicians may maximize treatment path, facilitate safe return-to-sport, and possibly minimize susceptibility to future knee injury.

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