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Human Kinetics
ORIGINAL RESEARCH REPORT

Prediction of 12-Month Clinical Outcomes Postsurgery Based on 3-Month Knee Examination After Primary Anterior Cruciate Ligament Reconstruction

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Context: Active management of modifiable factors during the early rehabilitation stage can help patients who have undergone anterior cruciate ligament (ACL) reconstruction successfully return to sports. This study aimed to determine predictors for performance on the single-leg hop test and Tegner activity score 12-month post-ACL reconstruction, based on knee function assessed 3-month postsurgery. ***Design:*** Prospective cohort study. ***Methods:*** Ninety-one patients who underwent ACL reconstruction were recruited. Multivariate logistic regression analysis was performed to identify predictors of the one hop test and Tegner activity score 12-month postsurgery, based on a knee examination performed 3 months after ACL reconstruction. Factors evaluated at 3 months included the Biodex balance system anteroposterior and mediolateral indexes; Y balance test anterior, posteromedial, and posterolateral reaches; knee extensors and flexors peak torque per body weight; and knee extensors and flexors average power per body weight. ***Results:*** The knee extensor peak torque per body weight (PT/BW) and Biodex balance system-mediolateral index with cutoff values of 132 N·m/kg and 0.45, respectively were identified as predictors for achieving a limb symmetric index within 10% on the hop test. Furthermore, achieving a Tegner activity score over 6 was predicted by Y balance test-posteromedial reach and knee flexors average power per body weight, with cutoff values of 92.5 cm and 122 W/kg, respectively. ***Conclusion:*** Three months following ACL reconstruction, knee extensor peak torque, and mediolateral balance predicted performance on the hop test, while dynamic posteromedial balance and knee flexors average power predicted rotational ability, at the 12-month assessment.

Keywords: balance, functional performance, muscle strength, rehabilitation

Key Points

- Knee functions at 12 months were predicted using 3-month assessment after anterior cruciate ligament reconstruction.
- Predictors for hop test were the knee extensor peak torque and mediolateral balance.
- Predictors for rotational ability were knee flexors power and posteromedial balance.

Return to sports (RTS) following anterior cruciate ligament (ACL) reconstruction is considered an indicator of successful surgery.[1] However, patients often experience knee muscle weakness following surgery due to hamstring harvest and quadriceps inhibition,[2] as well as compromised postural stability due to ACL mechanoreceptor injury.[3] These factors contribute to reduced physical function,[3,4] making it challenging for patients who have undergone ACL reconstruction. Therefore, the recovery of muscle strength, balance, and functional performance is crucial for successful RTS after surgery.[1,4]

To achieve successful and safe RTS, accurate assessment of physical function and establishment of clear criteria are particularly important. Various objective and subjective tests are performed for this purpose. Among them, the single-leg hop test and Tegner activity score are used as objective and subjective tests, respectively,[1] both of which determine when RTS is appropriate.[5] Generally, the RTS criteria encompass achieving a limb symmetric index (LSI) within 10% on the hop test[1] and a Tegner activity score exceeding 6 for pivoting sports.[5]

In addition to the test battery, several studies have identified factors that determine safe RTS. Most of these studies have focused on factors related to surgery or joint condition that cannot be modified through rehabilitation, such as age, graft diameter, medial meniscal resection, knee laxity, and posterior tibial slope.[6–8] However, during early rehabilitation after ACL reconstruction, patients often experience muscle weakness and reduced balance.[2–4] Modifiable factors, such as strength,[4] balance,[9] and abnormal biomechanical patterns,[3] can be addressed with rehabilitation. Proactively managing these modifiable factors during early rehabilitation can help patients who have undergone ACL reconstruction to achieve successful and safe RTS.

Rehabilitation primarily focuses on restoring range of motion, muscle strength, and balance during the first 3-month postsurgery. This 3-month postsurgery period is particularly

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critical in rehabilitation, typically marking the initiation of impact drills, such as double limb jumping and running, especially for athletes.[10] Therefore, predicting RTS outcomes based on data collected at this 3-month mark is imperative. Most previously published studies have sought to predict RTS based on preoperative factors,[11,12] nonmodifiable factors,[6–8,12] or factors at the 6-month mark.[13] However, few have prospectively predicted RTS based on modifiable factors at the 3-month postoperative stage.

This study aimed to determine the predictive factors of performance in the single-leg hop test and Tegner activity score at the 12-month mark, based on modifiable knee function data obtained at the 3-month post-ACL reconstruction assessment. We hypothesized that patients exhibiting good muscle strength, postural stability, and balance at the 3-month mark would achieve an LSI within 10% on the hop test and successfully engage in pivoting sports at 12-month postsurgery.

Methods

Study Design

For this study, 90 patients were recruited to meet the sample size, considering the regression rule of approximately 10 patients per 1 independent variable.[14] To obtain demographic and clinical characteristics, all the enrolled patients' medical records were reviewed retrospectively. A total of 9 independent and 2 dependent variables were analyzed. The 9 independent variables included the Biodex balance system (BBS)-anteroposterior and mediolateral indexes; Y balance test (YBT)-anterior, posteromedial, and posterolateral reaches; knee extensors and flexors peak torque per body weight (PT/BW); and knee extensors and flexors average power per body weight (AP/BW). The 2 dependent variables were the single-leg hop test and Tegner activity score.

Patients

This study was approved by the Ethics Committee of Inje University Seoul Paik Hospital (Institutional Review Board number PAIK 2023-02-009). The medical records of 91 patients who had undergone single-bundle anatomical ACL reconstruction were retrospectively reviewed between June 2016 and April 2022. The inclusion criteria for the study were patients aged 18–45 years who underwent single-bundle ACL reconstruction and completed all required tests at the 3-month and 12-month postsurgery intervals. The exclusion criteria encompassed patients with concomitant multiple ligament injury or fracture, patients who underwent meniscus root repair, cartilage repair, osteotomy for mechanical alignment correction, subtotal or total meniscectomy, revision ACL reconstruction, and those with a history of prior knee surgery on the involved and uninvolved side (Figure 1). Patient characteristics are outlined in Table 1.

Surgical Technique

Arthroscopic anatomic ACL reconstruction was performed using the outside-in technique with ipsilateral semitendinosus quadruple autografts, while preserving the remnants. The placement of the femoral and tibial tunnels was guided based on the anatomic center. The femoral tunnel was drilled using a flip cutter. Subsequent to the

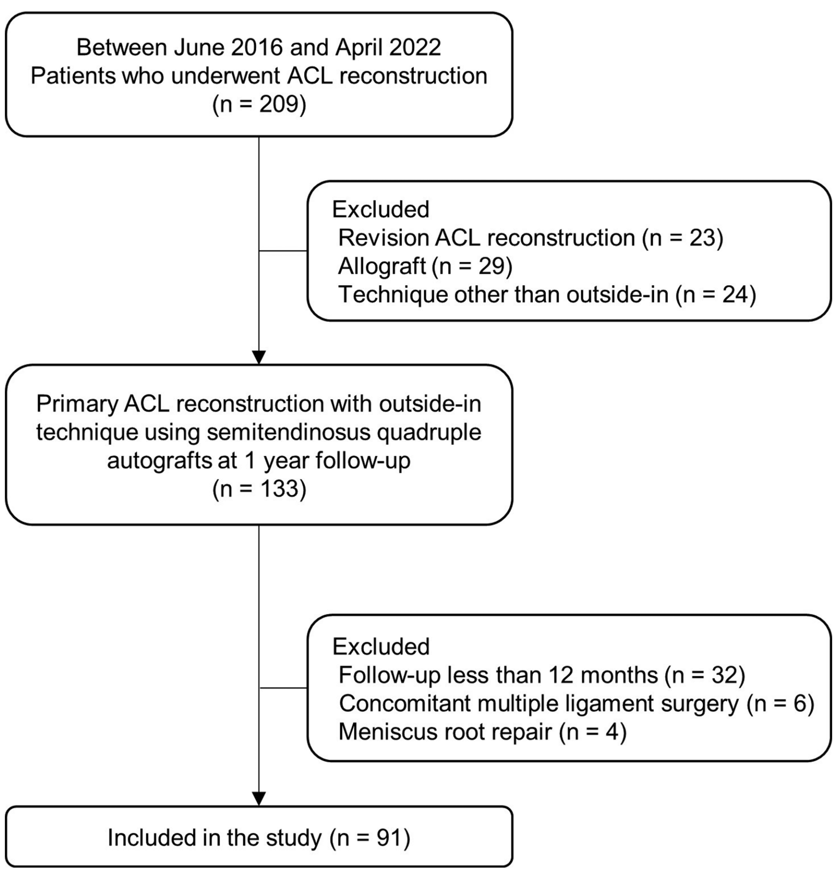

Figure 1 — Flowchart of study group enrollment. ACL indicates anterior cruciate ligament.

Table 1 General Characteristics

Participant characteristics (N = 91)	Mean (SD)
Age, y	28.9 (8.7)
Sex, male/female, n	60/31
Height, cm	171.8 (8.3)
Weight, kg	74.0 (12.7)
Body mass index, kg/m^2	24.9 (3.1)
Follow-up period, months	12.3 (2.2)

Note: Values are expressed as mean (SD).

creation of tunnels and graft passage, femoral fixation was achieved with a TightRope RT (Arthrex). Tibial fixation was performed using a hydroxyapatite interference screw (S&N Corp). Additional tibial fixation was achieved through post-tie fixation using a cortical screw.

Postoperative Rehabilitation

All subjects followed a standardized home-based rehabilitation program after ACL reconstruction. Within 1 or 2 days after surgery, they were able to tolerate weight bearing. For 3 weeks, the subjects wore an ACL support brace with full extension and used a crutch for support. By the end of the third week, full weight-bearing was allowed, and the brace was discontinued between 4 and 6 weeks postsurgery. Three months following surgery, light running and functional training were progressively introduced. By 6 months, RTS activities, excluding competition, were allowed.

Procedure

All testing was performed by one of the authors (X.X.X) at the 3-month and 12-month mark after ACL reconstruction. The order of the tests was randomized using an online application (www.randomization.com). The tests administered included the BBS test, YBT, isokinetic muscle strength test, and single-leg hop test, while the Tegner activity score was filled out.

Biodex Balance System Test

Postural stability was measured using the BBS (Biodex Medical Systems Inc), an apparatus consisting of a mobile platform with 12 levels of difficulty. For this study, level 8 resistance was set to measure postural stability. The BBS electronically generated metrics, including the anteroposterior index (sagittal plane) and mediolateral index (frontal plane), which were examined for this study, as well as the overall index. During the assessment, patients were instructed to stand on one leg with both hands placed on their chest while maintaining their balance at the center of the BBS monitor. Each assessment lasted for 30 seconds; 3 trials were conducted to ensure reliable measurements, with a 10-second rest interval between each trial. The values from all 3 trials were automatically recorded.

Y Balance Test

Dynamic balance was assessed using the YBT (Move2Perform). During the test, patients stood on their weight-bearing leg on a platform while gently pushing the side of a box using their non-weight-bearing leg. They extended their leg as far as possible in 3 directions: anterior, posteromedial, and posterolateral. Each patient underwent 6 practice trials to familiarize themselves with the task, followed by 3 measurement trials. Distances achieved in centimeters were recorded, averaged for each direction, and analyzed to assess dynamic balance.

Isokinetic Muscle Strength Test

The isokinetic muscle strength was measured using the HUMAC-NORM isokinetic extremity system (Computer Sports Medicine Inc). Measurements were taken while the patients were in a seated position, with angular velocities set at 60 and 180°/s. PT/BW and AP/BW for knee extensors and flexors were assessed at the respective angular velocities of 60 and 180°/s. To measure PT/BW, patients performed 4 repetitions of concentric quadriceps and hamstring contractions at 60°/s after 2 practice sessions within 90° to 0° (knee flexion). For AP/BW, contractions were repeated 10 times at 180°/s within the same knee flexion range after 2 practice sessions. The highest recorded data from the 4 repetitions of PT/BW and the AP calculated from the 10 repetitions of AP/BW were automatically recorded by the system.

Single-Leg Hop Test

During the single-leg hop test, patients assumed a standing position on the test leg and were instructed to hop forward as far as possible, landing on the same leg. The hop distance was measured in centimeters, measured from the toe's point of push-off to the heel's location at the time of landing. This test was conducted 3 times, and the greatest distance achieved during the single-leg hop test was analyzed.

Statistical Analyses

The Kolmogorov–Smirnov *Z* test was used to assess the normality of data distribution. Demographic statistics were calculated for sex, age, height, weight, and body mass index. Multivariate logistic regression was performed to determine the predictability of the single-leg hop and Tegner activity score at the 12-month postsurgery interval, based on the knee examination conducted at the 3-month mark following ACL reconstruction. The 2 targets of RTS (single-leg hop test and Tegner activity score) were converted into a dichotomous variable based on an LSI of less than 10% for the single-leg hop test and a Tegner activity score of over 6 points. The predictive model performance was classified based on the area under the receiver-operating characteristic (ROC) curve (AUC) value, with categories ranging from excellent (≥0.9), good (0.8–0.9), fair (0.7–0.8), and poor (<0.7).[12] To determine the cutoff values for the independent factors, ROC analysis with a calculation of the AUC was performed. All statistical analyses were performed using the SPSS software (version 22.0 for Windows), and the statistical significance was set at 5% ($P < .05$).

Results

Single-Leg Hop Test

Knee extensors PT/BW and the BBS mediolateral index 3 months after ACL reconstruction were significant predictors of a LSI within 10% on the hop test at the 12-month postsurgery mark. The knee examination conducted 3-month postsurgery accounted for 30.1% of the variance in the outcomes at the 12-month mark postsurgery ($P = .013$; Table 2). For predicting LSI within 10% on the hop test, the ROC curves identified cutoff values of 132 N·m/kg for knee extensors PT/BW (sensitivity of 56% and specificity of 88%) and 0.45 for the BBS mediolateral index (sensitivity of 86% and specificity of 16%) (Table 3).

Table 2 Three-Month Post-ACL Reconstruction Predictors for Limb Symmetric Index Within 10% on the Hop Test at 12 Months Postsurgery (R^2: Nagelkerke R^2, OR, and 95% CI)

Independent variables	R^2	OR	95% CI	P
Knee extensor PT/BW	.301	1.025	1.012–1.039	.001
BBS mediolateral index		0.235	0.067–0.828	.024

Abbreviations: ACL, anterior cruciate ligament; BBS, Biodex balance system; CI, confidence interval; OR, odds ratio; PT/BW, peak torque per body weight.

Table 3 AUC and Cutoff Values of Predictors of Performance in the Single-Leg Hop Test

Variable	AUC	SE	P	95% CI	Cutoff value
Knee extensor PT/BW	0.728	0.052	.001	0.625–0.831	132 N·m/kg
BBS mediolateral index					0.45

Abbreviations: AUC, area under the receiver-operator characteristic curve; BBS, Biodex balance system; CI, confidence interval; PT/BW, peak torque per body weight.

Tegner Activity Score

YBT-posteromedial reach and knee flexors AP/BW 3 months after ACL reconstruction were significant predictors of a Tegner activity score >6 points postsurgery. The knee examination 3 months after ACL reconstruction accounted for 26% of the variance in outcomes at the 12-month mark postsurgery ($P = .034$; Table 4). To predict a Tegner activity score >6 points, ROC curve analysis identified cutoff values of 92.5 cm for YBT-posteromedial reach (sensitivity of 51% and specificity of 84%) and 122 W/kg for knee flexors AP/BW (sensitivity of 51% and specificity of 88%) (Table 5).

Table 4 Predictors at 3 Months After ACL Reconstruction for Achieving a Tegner Activity Score >6 at 12 Months Postsurgery (R^2: Nagelkerke R^2, OR, and 95% CI)

Independent variables	R^2	OR	95% CI	P
YBT-PM	.257	1.068	1.002–1.137	.043
Knee flexors AP/BW		1.034	1.030–1.059	.005

Abbreviations: AP/BW, average power per body weight; ACL, anterior cruciate ligament; CI, confidence interval; OR, odds ratio; YBT-PM, Y balance test—posteromedial.

Table 5 AUC and Cutoff Values for Predictors of the Tegner Activity Score

Variable	AUC	SE	P	95% CI	Cutoff value
YBT-PM	0.743	0.052	.001	0.640–0.846	92.5 cm
Knee flexors AP/BW					122 W/kg

Abbreviations: AUC, area under the receiver-operator characteristic curve; AP/BW, average power per body weight; CI, confidence interval; YBT-PM, Y balance test—posteromedial.

Discussion

While several studies have reported predictors for RTS time, to the best of our knowledge, few have focused on predicting functional abilities in the late rehabilitation stage based on factors from the early rehabilitation stage. The main finding of this study was that functional abilities in the late rehabilitation stage can be predicted based on modifiable factors during the early rehabilitation stage. Specifically, following ACL reconstruction, achieving an LSI within 10% on the hop test at 12-month postsurgery relies on predictors such as knee extensors PT and ability to maintain mediolateral balance during one-leg stand at the 3-month postoperative mark. Likewise, participating in pivoting sports at 12-month postsurgery relies on predictors such as AP of knee flexors and ability to maintain posterolateral balance during one-leg stand at the 3-month postoperative mark.

Previous studies have predominantly used nonmodifiable factors or preoperative data.[6–8,11,12] For instance, in the study by Ye et al,[12] predictors of a return to preinjury sports included young age, high preoperative International Knee Documentation Committee score, and large graft diameter (AUC, 0.773 [fair]; accuracy, 70.5%) while predictors of a return to pivoting sports encompassed young age, male sex, participation in competitive sports, high preoperative International Knee Documentation Committee score, and large graft diameter (AUC, 0. 777 [fair]; accuracy, 69.2%). In the study by Takuya using preoperative data, preoperative quadriceps strength was found to be a predictor of RTS (AUC, 0.74 [fair]; sensitivity, 68.9%; specificity, 77.3%; cutoff, 66%).[11] In contrast, our study used data at the 3-month postoperative mark, which is a modifiable factor and a crucial transition point in the rehabilitation process. The results of the current study showed comparable AUC and accuracy compared with previous studies. Predictors of LSI within 10% on the hop test included knee extensors PT/BW and BBS mediolateral index (AUC, 0.728 [fair]; accuracy, 74%; cutoff, 132 N·m/kg and 0.45, respectively). The predictors for achieving a Tegner activity score over 6 were YBT-posteromedial reach and knee flexors AP/BW (AUC, 0.743 [fair], accuracy, 69%; cutoff, 92.5 cm and 122 W/kg, respectively).

Knee extensors PT at the 3-month mark postsurgery was a significant predictor of hop performance at the 12-month assessment following ACL reconstruction. Several studies have reported that the strength of the hip extensors, quadriceps, and triceps surae muscles is crucial for achieving both long and high jumps.[15,16] In particular, quadriceps strength is essential for hop ability and plays a significant role in injury prevention.[17]. However, despite the critical role of the quadriceps, it is susceptible to weakening postsurgery due to several factors. The quadriceps femoris muscle can weaken after ACL reconstruction because of various factors, of which the primary one is the prolonged inability to fully activate the quadriceps muscle or arthrogenic muscle inhibition.[18] Additionally, another contributing factor is restricted knee motion (50°–100°) during strengthening exercises, which prevents tibial anterior translation; however, it can further exacerbate quadriceps muscle weakness during the early stages of rehabilitation.[19] Nonetheless, quadriceps strength is essential for hop ability and plays a significant role in injury prevention. Several previous studies have emphasized the significance of quadriceps recovery in the process of RTS,[20,21] and this study has yielded comparable findings. Moreover, the hop test serves as a critical indicator for determining readiness to RTS activities.[22] Therefore, the recovery of quadriceps strength after ACL reconstruction is imperative to ensure a safe and successful RTS.

Assessment of the knee flexors AP 3 months after ACL reconstruction was a significant predictor for pivoting activity at the 12-month mark following ACL reconstruction. The knee flexor, especially the hamstring, contributes significantly to knee stability as dynamic stabilizers and synergists of the ACL.[23] Moreover, it contributes significantly to preventing the tibia from moving forward.[24] However, patients who undergo ACL reconstruction using a semitendinosus autograft experience hamstring weakness due to graft harvest.[2] The hamstring is responsible for controlling tibial rotation during pivot movements,[25] underscoring the importance of regaining hamstring strength for engaging in pivoting sports. In this study, the AP of knee flexors was used as a variable instead of PT, considering the importance of sustaining power rather than momentary force during pivoting sports.

Mediolateral balance at the 3-month mark was a significant predictor for hop test performance at the 12-month assessment post-ACL reconstruction. Among the various causes of ACL injury, knee valgus is a recognized primary factor.[26] Dynamic knee valgus can be influenced by a pronated foot position,[27] leading to poor mediolateral balance in affected patients and is often observed during landing. In a study by Hewett et al,[28] landing with the knee in abduction (ie, valgus) was identified as a risk factor for noncontact ACL injury. The study suggests that improved mediolateral balance could positively affect dynamic knee valgus during landing, potentially reducing the fear of reinjury and enhancing hop ability. Consequently, incorporating balance training during rehabilitation for post-ACL reconstruction becomes crucial.[29] However, it should be noted that while traditional balance training, such as double-leg balance, single-leg balance, and perturbation exercises, as reported by Paterno et al,[29] primarily enhance anteroposterior stability, these training exercises do not target mediolateral stability. Therefore, since well-structured balance training programs reduce knee abduction moments,[30] developing specific balance training exercises targeting mediolateral balance is essential to improve hop ability effectively.

YBT-posteromedial reach at the 3-month rehabilitation stage was a significant predictor for pivoting activity at the 12-month assessment following ACL reconstruction. Among the mechanisms contributing to AC injury, the application of external impulsive axial force on the knee joint is a primary mechanism.[26] The contact area between the articular surfaces is notably greater on the medial side of the knee joint than on the lateral side.[31] When contact occurs between the flatter anterior portion of the lateral femoral condyle and the convex lateral tibial plateau, the knee tends to favor sliding (ie, pivot shift) over rolling.[32] Consequently, controlling knee joint movements becomes more challenging when the opposite leg reaches a posteromedial direction. Moreover, compared with other movements, the posteromedial direction involves less activation of the hip external rotators[33] and increases knee movement in the frontal plane,[34] imposing greater strain on the knee. However, if this movement can be well controlled, as suggested by the findings of this study, it could offer advantages for engaging in pivoting sports. Therefore, balance training pertaining to knee posteromedial reach would be necessary for individuals interested in participating in pivoting sports.

This study has few limitations. First, the sample size was relatively small, which may limit the generalizability of the findings. Second, there was an uneven distribution of male (66%) and female (34%) participants. Third, the study relied exclusively on the single-leg hop test and Tegner activity score to determine RTS readiness, without considering other relevant measures. Fourth, variations in participants' physical abilities were not factored into the analysis. Although the study included participants aged 18–45 years, significant differences in activity levels and physical abilities may affect functional task performance. Fourth, the analysis did not account for whether the dominant or nondominant leg was not tested, which could influence balance and the hop scores. Future studies should include a longitudinal follow-up study to validate whether incorporating the identified variables into 3-month training postsurgery improves physical function at the 12-month mark.

Conclusions

The predictors for the 12-month straight jump performance after ACL reconstruction, based on data from the 3-month assessment, were knee extensor PT and one-leg mediolateral balance. Furthermore, predictors of 12-month rotational ability were dynamic one-leg posteromedial balance and knee flexors AP. Thus, incorporating exercises to enhance knee extensor strength, knee flexor endurance, single-leg medial-lateral balance, and single-leg dynamic posteromedial balance during the early stages of rehabilitation is important.

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