Hamstring Strength Recovery in Relation to Landing Patterns Following Anterior Cruciate Ligament Reconstruction: A Case Comparison Report

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ABSTRACT

Introduction: Deficits in quadriceps strength following anterior cruciate ligament reconstruction (ACLR) are common and can be associated with biomechanical asymmetries during landing tasks. The relationship between quadriceps strength and knee function during ACLR recovery is well established. However, less is known regarding the role of hamstring strength in functional recovery after ACLR. We examined movement patterns during a drop-landing task in three patients following ACLR with different levels of quadriceps and hamstring strength.

Methods: Three participants were assessed for quadriceps and hamstrings strength, functional performance, and lower-extremity biomechanics captured by a 3D motion analysis 6 months after ACLR.

Results: Participant one, who presented with relatively recovered quadriceps and hamstring strength of the operated limb, demonstrated the highest limb symmetry indices across multiple tests compared to the other two participants. Participant two, who had insufficient recovery in quadriceps strength yet preserved hamstring strength, demonstrated similar recovery in drop-landing mechanics than participant one and a lower overall hop performance than participant one. Participant three, who had residual deficits in both quadriceps and hamstring strength, exhibited the largest asymmetries in overall hop performance, vertical ground reaction force, and knee flexion angle upon bilateral landing.

Conclusion: This study suggests that quadriceps strength alone does not account for variability in functional recovery and altered biomechanics following ACLR. It is important to evaluate both quadriceps and hamstring strength as indicators for functional recovery and readiness for return to sport after ACLR.

Keywords: Anterior Cruciate Ligament Reconstruction, Functional Performance, Muscle Strength Dynamometer, Hamstring Muscles, Quadriceps Muscles

INTRODUCTION

Injury to the anterior cruciate ligament (ACL) is common among competitive athletes.[1] ACL reconstruction (ACLR) reflects the mainstay of treatment for ACL injuries in athletes, with the goals of promoting a safe return to sport and restoring knee stability and kinematics.[2,3] However, many athletes undergoing ACLR fail to achieve pre-injury activity levels. A recent meta-analysis suggested that nearly half of individuals do not reach pre-injury activity levels following ACLR,[4] and the likelihood of return to sport may be as low as 19.0% in certain athletic populations.[5] A variety of factors may limit functional recovery, including age,[4,6] impaired quadriceps strength of the injured limb, altered biomechanics,[4,7,8] and psychological responses.[9-11]

Following ACLR, recovery of quadriceps strength of the injured limb is often used as one of several clinical factors to gauge readiness for return to sport.[8,12] Yet, only about 20.0% of patients can achieve near symmetric quadriceps strength by 6 months after ACLR,[7,13] and some patients demonstrating persistent ipsilateral quadriceps weakness as long as 5 years after ACLR.[14,15] Recovery and symmetry of functional movement have also been used to assess readiness for return to sport. The Landing Error Scoring System (LESS) test has been established to evaluate the risk of ACL injury and clarify the appropriateness of return to sport after ACLR.[16] Kuenze et al[17] suggested that residual quadriceps weakness may be associated with impaired functional movement and lower LESS scores. Other studies have indicated that quadriceps weakness after ACLR is associated with reduced knee joint moments and ground reaction forces, which is known as the "stiff" knee landing pattern.[7,18] This pattern can contribute to excessive knee valgus and increased torsional forces, subsequently placing undesirable stress on the reconstructed ACL.[19,20] Consequently, quadriceps strength and lower-extremity biomechanics have become pivotal in promoting and predicting return to pre-injury activity levels, including sport.[4,6,9,10,21]

While significant research has focused on quadriceps strength, hamstring strength is also likely to influence lower-extremity biomechanics and successful return to sport after ACLR. Insufficient hamstring recovery in the injured limb has been reported in up to 50.0% of patients undergoing ACLR.[13,22] Blackburn et al[23] reported that higher hamstring viscoelasticity may be associated with reduced anterior tibial shear forces and lower peak knee valgus moment during landing, which may, in turn, lower the risk of ACL injury. There remains a relative lack of evidence to explain the biomechanical role of hamstring strength in predicting clinical outcomes, including return to competition following ACLR. This case comparison report is designed to examine different movement patterns during landing tasks according to the varying recovery of both quadriceps and hamstring strength after ACLR. We hypothesized that the greater strength of both muscles would be associated with improved landing patterns.

METHODS

Participants

We evaluated three competitive athletes between the ages of 21 and 23 years who sustained an ACL tear and underwent ACLR (Table 1). Participant one was primarily reconstructed with a quadriceps tendon autograft using a bone plug. Participant two initially underwent bone-patellar tendon-bone autograft and subsequently required revision with a soft-tissue quadriceps tendon autograft. Participant three was managed primarily with a soft-tissue quadriceps tendon autograft. Participant three also suffered a simultaneous medial collateral ligament (MCL) tear that was reconstructed with a hamstring tendon autograft.

The three participants were differentiated by lower-extremity strength 6 months after ACLR. Quadriceps and hamstring strength were assessed by maximal voluntary isometric contraction using a dynamometer (Biodex Medical Systems, Inc; Shirley, NY). Strength testing was performed bilaterally, with the participant seated, the hip flexed to 110°, and the knee flexed to 90°. The hip flexion and knee flexion angles were standardized and set on the Biodex dynamometer for all participants. Participants were provided with up to three submaximal practice trials. Peak torque over a 5-second contraction was then recorded for three trials with a 1-minute rest between trials to minimize fatigue. As per standard protocol, the highest value among the three trials was used for the analysis. Quadriceps and hamstring strength of the injured and non-injured limbs were recorded.

Testing Procedures

In addition to muscle-strength testing as outlined previously, all participants underwent functional movement assessment and biomechanical motion analysis 6 months postoperatively. Participants performed all physical testing wearing their own athletic footwear.

Functional Movement Assessment

Functional movement assessment included timed lateral step-down, lateral leap and catch, square hop test and hop sequences (ie, timed hop, single-leg hop, triple hop, and crossover hop). All included tests have established test-retest reliability and are often used in clinical settings.[24-26] All participants were supervised during testing, and they were provided with adequate rest to prevent fatigue or missteps during testing.

Biomechanical Assessment

A ten-camera Vicon Motion Capture System with Vicon Nexus software (Vicon Motion Capture Systems Ltd; Oxford, UK) synchronized with three force plates (AMTI; Watertown, MA) captured each participant's torso and lower extremity during a drop-landing maneuver. Kinematic and kinetic data were integrated for simultaneous collection at 100 Hz and 1000 Hz, respectively. Additionally, two digital cameras (Vicon Motion Capture Systems Ltd; Oxford, UK) were used in the frontal and sagittal planes to determine functional quality during the drop-landing task. A total of 48 reflective markers (14 mm diameter) were placed on bony prominences to determine the center of each joint and the end of individual body segments, based on 6° of freedom as previously reported.[27] We performed a standing calibration to define joint centers and distinguish a coordinate system for each body segment before motion analysis.

Each participant was recorded while performing a double leg drop jump from a 30-cm step. A total of three usable attempts were recorded for each participant. Participants were instructed to drop off of the box with both feet simultaneously, land with each foot on separate force plates, and then immediately perform a maximal effort vertical jump in place.[28]

Data Analysis

A post-capture analysis was conducted (Visual 3D; Germantown, MD) to calculate joint kinematics and kinetics. A post-capture analysis was conducted (Visual 3D; Germantown, MD) to calculate joint kinematics

Table 1. Isometric Muscle Strength and Limb Symmetry Indexes[a]

	Participant 1	Participant 2	Participant 3
Age	21 years	23 years	21 years
Gender	Female	Female	Female
Body Mass Index (kg/m2)	18.6	27.2	21.5
Graft Type	Quadriceps autograph with bone plug	Primary: Patella BTB autograph Revision: Soft tissue quadriceps auto	Soft tissue quadriceps autograph MCL with hamstring autograph
Participated Sports	soccer	rugby	rugby
Quadriceps			
MVIC Operated (N•m)	98.3	43.9	53.3
MVIC Non-operated (N•m)	135.4	239.3	125.6
LSI	72.6%	18.3%	42.4%
Hamstrings			
MVIC Operated (N•m)	67.3	53.7	19.4
MVIC Non-operated (N•m)	73.2	55.2	72.5
LSI	91.9%	97.3%	26.8%
Injured Hamstrings Quadriceps Index	68.46%	122.32%	36.40%

kg/m^2, kilogram per meter square; MVIC, maximum voluntary isometric contraction; N•m, newton meters; LSI, limb symmetry index

[a]The hamstrings quadriceps index is a value of strength comparing the quadriceps strength to the hamstrings strength in the operated limb for each participant.

and kinetics. Microsoft Excel (Microsoft Corporation; Redmond, WA) was used for statistical analysis. Descriptive statistics were used to compare functional movement scores and biomechanical measures across participants. A limb symmetry index (LSI) was calculated for strength and hop sequence performance as the injured limb result divided by the non-injured limb result multiplied by 100 ($LSI = \frac{\text{injured limb result}}{\text{non-injured limb result}} \times 100$). The hamstrings quadriceps index was calculated for the injured limb as hamstring strength divided by quadriceps strength multiplied by 100 ($\text{hamstrings quadriceps index} = \frac{\text{hamstrings maximum voluntary isometric contraction (MVIC)}}{\text{quadriceps MVIC}} \times 100$)

RESULTS

Quadriceps and Hamstring Strength

Participant one demonstrated relatively symmetric quadriceps and hamstring strength between injured and non-injured limbs. Participant two demonstrated significantly reduced quadriceps strength of the injured limb but relatively symmetric hamstring strength. Participant three demonstrated significantly reduced quadriceps and hamstring strength of the injured limb. The classification for each case based on the quadriceps and hamstring strength is presented in Table 1.

Functional Movement Assessment

For the affected limb, limb symmetry indices for the timed hop, triple hop distance, crossover hop distance tests, and mean hop performance across the three tests are reported in Table 2. Participant one showed relative symmetry during functional movement assessment, with hop performance LSIs between 84.0% to 108.0% and an overall mean hop performance LSI of 91.0%. Participant two demonstrated hop performance LSIs between 71.0% to 88.0%. Participant three demonstrated the greatest limb asymmetry during timed hop, triple hop, and crossover hop tests, with LSIs between 54.0% to 56.0%.

Biomechanical Analysis

For the drop-landing task, all three participants showed significantly lower vertical ground reaction forces through their injured limb following ACLR (Figure 1). Data collected for knee kinematics during

Table 2. Hop Performance Limb Symmetry Indices[a]

Assessment	Participant 1	Participant 2	Participant 3
Timed Hop	87.19%	71.43%	54.04%
Triple Hop Distance	84.51%	73.39%	53.97%
Crossover Hop Distance	83.99%	84.69%	56.21%
Overall Hop LSI	91.00%	79.56%	88.81%

LSI, limb symmetry indices

[a]The limb symmetry index (LSI) between injured and non-injured limbs of each subject for each of the 4 hop performance measures as well as overall hop performance.

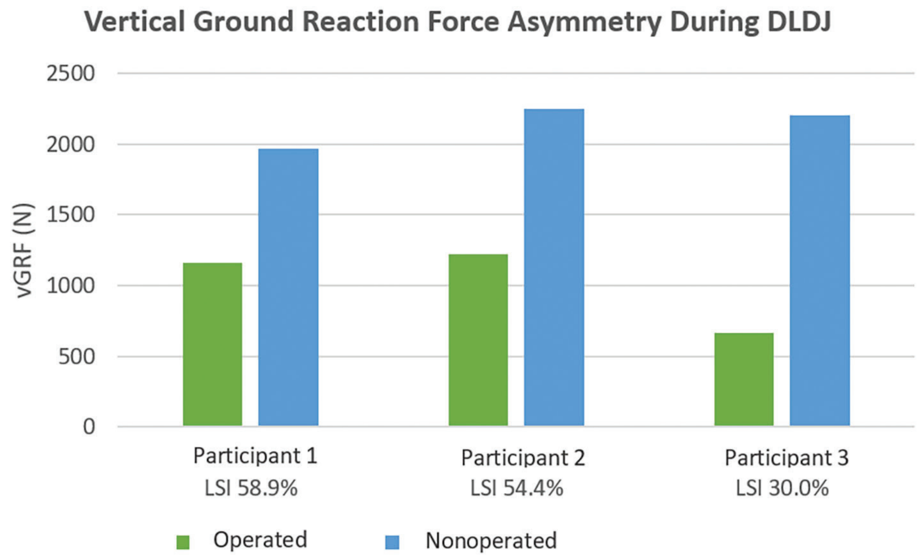
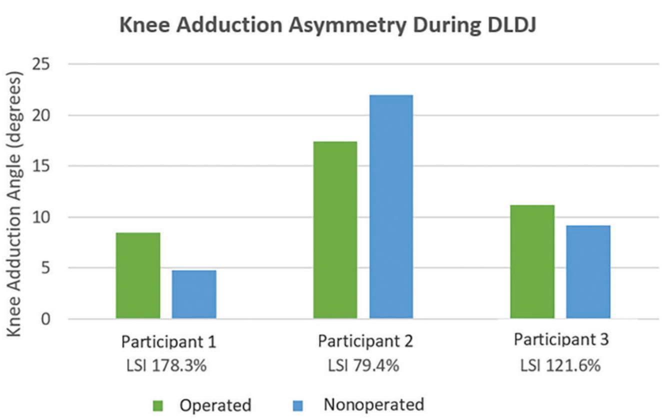


Figure 1. *Vertical ground reaction force asymmetry during landing. The vertical ground reaction force at initial landing was obtained for the operated and non-operated limb with a limb symmetry index calculated for each subject. vGRF, vertical ground reaction forces; N, newtons; LSI, limb symmetry index*



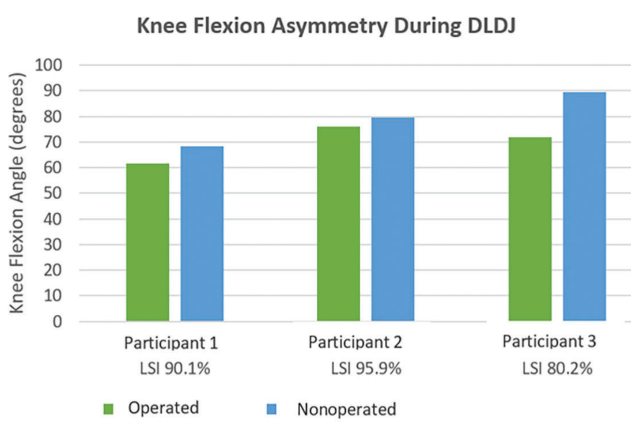


Figure 2. *Knee flexion and adduction asymmetry during landing. Participants two and three demonstrated increased knee flexion with asymmetry adduction during the landing. LSI, limb symmetry index*

the drop-landing task are shown in Figure 2. All three participants demonstrated reduced peak knee flexion of the injured limb when compared to the non-injured limb. Participants one and two exhibited substantially greater limb symmetry in knee flexion, with LSI greater than 90.0% compared to participant three (LSI, 80.0%). In addition, participants one and three demonstrated higher peak knee adduction angles of the injured limb when compared to the non-injured limb. Participant two exhibited greater peak knee adduction angles of both the injured and non-injured limbs when compared to the other two participants; however, knee adduction angles were relatively greater on the non-injured limb when compared to the injured limb.

DISCUSSION

In this study, we analyzed the functional and biomechanical characteristics of three competitive athletes 6 months after they underwent ACLR with different grafts. Despite established clinical expectations, all participants demonstrated inter-limb asymmetry during hop performance tests (LSI, 79.6%-91.0%). Patterns of inter-limb asymmetry were apparent across all hop tests, except the single-leg hop for distance test. Cristiani et al[13] found no correlation between quadriceps or hamstrings LSI greater than or equal to 90.0%. The single-leg hop test performance could explain why the participants demonstrated high variability when performing this test despite three distinct strength presentations. Excluding single-leg hop test for distance, mean limb asymmetry indices for hop performance were 82.5% for participant one, 76.5% for participant two, and 54.7% for participant three.

An interesting finding in this case series is the apparent influence of persistent hamstring weakness on functional and biomechanical outcomes after ACLR. Overall hop performance symmetry declined from participants one to three as the quadriceps and hamstring strength symmetry also declined. Similarly, vertical ground reaction force and peak knee flexion symmetry decreased with decreasing quadriceps and hamstring strength symmetry. It is important to note that participant three had a concurrent MCL reconstruction utilizing a hamstring autograft, which may have contributed to more severely reduced hamstring strength and LSI. The more extensive surgical intervention in participant three may have also resulted in a slower recovery trajectory than participants one and two, accounting in part for lower overall strength at 6 months postoperatively. Regardless, the fact remains that relative hamstring strength appears to influence functional performance following ACLR. Konrath et al[29] showed deficits in hamstring muscle size and knee flexion strength 2 years after ACLR with a hamstring autograft. Another recent study compared short-term Biodex strength results among three groups (ie, quadriceps graft, bone-patella tendon-bone graft, and hamstring graft) following ACLR.[30] The authors demonstrated that persistent quadriceps or hamstring tendon weakness following quadriceps tendon or hamstring ACLR, respectively, may last up to 15 months. These results indicate that current rehabilitation, including graft-specific protocols incorporating neuromuscular training, is inadequate despite established evidence-based protocols.[31-33]

Our findings are consistent with previous studies demonstrating an association between quadriceps strength, functional performance, and biomechanical performance across dynamic tasks.[17,34] Our findings add to the current literature by suggesting that quadriceps strength alone does not account for variability in functional and biomechanical measures following ACLR. Recovery of hamstring strength also plays an important role in determining functional restoration. We reviewed “accelerated” ACLR rehabilitation protocols prescribed by orthopaedic surgeons and found many surgeons begin quadriceps sets immediately after surgery. They also focus on gaining quadriceps strength within the first 4 to 6 weeks following surgery to allow for full weight bearing without any bracing. There is no mention of strengthening hamstrings in some of these protocols until 4 to 6 weeks following surgery. While some protocols mention no active range of motion or strengthening of hamstrings for a period of time following a hamstrings autograft, other protocols using alternate graft options still do not incorporate hamstrings strengthening until at least 1 month after surgery. Although better functional outcomes and symmetrical landing maneuvers are significantly correlated with the quadriceps strength of the operated limb, obtaining greater than 90.0% quadriceps strength symmetry is only one piece to the puzzle related to a safe return to sport. Because varied physical therapy protocols exist, the standardized evaluation and plan of care remain controversial.

For example, many clinics are not able to measure accurate quadriceps strength due to the required expensive equipment (ie, isokinetic dynamometer). Yet, recent studies describe excellent reliability in quadriceps strength assessments through a hand-held dynamometer and introduce valid functional performance-based tests to assess quadriceps strength, which could become reasonable options for clinicians. Additionally, some evidence-proven interventions are not routinely applied, such as neuromuscular electrical stimulation and open-chain exercises.[35,36] As shown in the current study, hamstring strength also needs to be a critical focus and regularly assessed, particularly for hamstring autograft patients.

Limitations

Due to the recruitment process, these three participants underwent varied surgical techniques, including graft selection. Postoperative rehabilitation was not standardized. Thus, we cannot rule out differences in the surgical approach or the rehabilitation process as factors influencing observed strength, functional performance, and biomechanics across participants. The site of autograft harvesting in each participant and concurrent MCL reconstruction in participant three are important to note. All three participants had an autograft harvested from their quadriceps. However, participant two initially had a bone-patellar-tendon-bone graft performed, and participant three had a hamstring autograft harvested for MCL reconstruction. We would suspect all three participants have affected quadriceps function, but the additional procedures performed on participants two and three may have contributed to the functional outcome measures observed at the time of testing. Furthermore, a hamstring-only graft reconstruction was not used in this small case series. Due to the small sample size, it is unknown if these results are generalizable to all ACLR patients.

Despite these limitations, our findings suggest that the restoration of both quadriceps *and hamstring* strength is critical to achieving optimal functional and biomechanical outcomes following ACLR. Further research with a larger sample size will provide further insight regarding the role of quadriceps and hamstring recovery and graft-specific rehabilitation protocols to optimize outcomes and return to sport following ACLR.

This case study suggests that quadriceps strength alone does not account for variability in functional recovery and altered biomechanics following ACLR. It is important to evaluate both quadriceps and hamstring strength as indicators for functional recovery and readiness for return to sport after ACLR.

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