Improvements in Thigh Strength Symmetry Are Modestly Correlated With Changes in Self-Reported Function After Anterior Cruciate Ligament Reconstruction

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Background: The association between quadriceps strength and functional outcomes after anterior cruciate ligament reconstruction (ACLR) is a focus of current research, while evaluations of hamstring strength are limited, despite the frequent use of hamstring autografts.

Purpose/Hypothesis: The purpose of this study was to determine the relationship between changes in quadriceps and hamstring strength symmetry and self-reported outcomes before ACLR and at 12 and 24 weeks after surgery. We hypothesized that improvements in quadriceps and hamstring strength symmetry would be correlated with improvements in self-reported outcome measures within the first 6 months after ACLR.

Study Design: Cohort study; Level of evidence, 2.

Methods: Thirty patients who underwent ACLR with a hamstring autograft were enrolled. Quadriceps and hamstring strength and Knee injury and Osteoarthritis Outcome Score (KOOS) values were assessed before and at 12 and 24 weeks after ACLR; limb symmetry indexes for strength were calculated at each time point. The Friedman and Wilcoxon signed-rank tests were used to analyze changes in KOOS values over time. Spearman rank-order correlations were used to test the relationship between changes in strength and KOOS values between each time point.

Results: Hamstring and quadriceps limb symmetry significantly increased with time ($P \leq .03$). Fair correlations were observed between changes in the hamstring index and changes in the KOOS Symptoms subscore from before surgery to 12 weeks postoperatively ($r = 0.48$; $P \leq .05$). Changes in the quadriceps index (QI) were moderately correlated with changes in the KOOS Sport/Recreation subscore ($r = 0.60$; $P = .001$), and fair correlations were seen between the QI and the KOOS Quality of Life subscore ($r = 0.39$; $P \leq .04$) from preoperatively to 12 weeks after surgery. Moderate correlations were seen between the QI and the KOOS Sport/Recreation subscore ($r = 0.57$; $P = .005$) from 12 to 24 weeks after surgery.

Conclusion: Improvements in quadriceps and hamstring strength symmetry were modestly associated with improvements in athletes' perceived function in the first 6 months after ACLR. Specifically, improvements in hamstring symmetry were associated with improvements in knee symptoms within the first 12 weeks postoperatively, while improvements in quadriceps symmetry were associated with improvements in self-reported sport function throughout the first 6 months after ACLR. The restoration of strength symmetry within the first 6 months may be a critical component of rehabilitation aimed at maximizing function after ACLR. Further investigation is warranted to comprehensively evaluate whether the timing of strength gains predicts future function, including those who successfully return to their preinjury activity level after ACLR.

Keywords: ACL; quadriceps strength; hamstring strength; self-reported knee function

Anterior cruciate ligament (ACL) reconstruction (ACLR) is frequently performed to restore knee stability after an ACL tear.[10,34] However, the recovery of sport-related function after ACLR varies significantly, and some athletes never return to their prior level of function.[30,37,48] Criterion-based

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rehabilitation aims to restore sport-related function; however, impairments such as decreased range of motion,[42,47] quadriceps and hamstring muscle weakness,[12,39,56] gait abnormalities,[17,44] and changes in neuromuscular activation patterns[44,49] persist, with some impairments lasting up to 2 years.[46,51] Muscle impairments, in particular, are associated with altered knee biomechanics and knee function and thus are important elements of focus in rehabilitation.[1,21,46]

The majority of studies have evaluated the recovery of muscle strength beginning at 6 months after ACLR.[11,25,32,46,52,55] However, studies on the relationship between quadriceps and hamstring strength and knee function in the first 6 months after ACLR are limited. During this time frame, rehabilitation progression includes the initiation of high-impact activities such as running and plyometrics.[2,8,34] It is well documented that performing high-impact activities with insufficient quadriceps strength can lead to abnormal joint loads[31,53] and asymmetrical dynamic knee function.[46] However, the relationship between hamstring strength and knee function is not as well established.

The hamstring muscle group provides inherent stability to the knee joint as an agonist to the ACL.[6,14] When hamstring grafts are utilized for ACLR,[36] hamstring weakness may occur, and despite improvements in strength over time, hamstring strength may not return to preoperative levels.[13,23,30] Hamstring strength and activation are associated with abnormal jumping kinematics in healthy controls[54] and a risk for primary ACL ruptures[34]; however, data regarding the association between hamstring strength and knee function after ACLR are conflicting.[1,15,24,26,29,51]

A large variation in the timing of successful return to sport is common after ACLR and implies that not all athletes recover at the same rate.[4] High-impact activity progression is a critical part of rehabilitation but may not be appropriate for some athletes who are not meeting strength milestones during this time frame. Identifying knee strength and functional deficits early in the rehabilitation process may allow for more directed interventions to help prevent delayed recovery and improve metrics at the time of return to sport.

Therefore, the purpose of this study was to determine the relationship between changes in quadriceps and hamstring limb symmetry and self-reported outcomes before ACLR and at 12 and 24 weeks after ACLR. We hypothesized that improvements in quadriceps and hamstring limb symmetry would correlate with improvements in self-reported outcome measures in the first 6 months after ACLR.

METHODS

Participants

Patients between the ages of 14 and 50 years with acute, primary, unilateral ACL ruptures were identified from an ongoing randomized controlled trial (RCT).[33] All participants from the parent RCT were included in this study, and all tests were part of the RCT protocol. An institutional review board approved this study protocol, and eligible participants and/or guardians provided informed consent. Patients were eligible to participate in the study if they participated in International Knee Documentation Committee (IKDC) level I/II cutting, pivoting, jumping, and lateral movement sports for at least 50 hours per year before their injury.[10,18] Participants had no history of lower extremity or lumbar spine injuries that required surgery or immobilization. Patients were excluded if they had concomitant injuries including contralateral ACL ruptures, chondral defects requiring surgical treatment, or concurrent grade III ligamentous injuries. Patients with meniscal tears were included, and the surgical procedure was documented.

Surgical Procedure and Postoperative Rehabilitation

Arthroscopic, anatomic, single-bundle ACLR was performed using a hamstring autograft by 1 of 3 sports medicine fellowship–trained surgeons (R.A.M., D.C.F., or C.C.K.). Femoral fixation was achieved using a cortical button, and tibial fixation was performed with an interference screw with or without a sheath device. Tourniquets were not utilized during the procedure. No postoperative bracing was used. Patients initiated formal rehabilitation within 1 week of surgery at a single physical therapy practice. After surgery, athletes were individually progressed through rehabilitation utilizing guidelines based on the Multicenter Orthopaedic Outcomes Network (MOON) recommendations.[28,59,60] Rehabilitation progression was adjusted based on the surgical procedure and strength, range of motion,

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effusion, and self-reported knee function milestones. Weightbearing was initiated immediately after surgery. Patients who underwent meniscal repair did not initiate weightbearing until 4 weeks after ACLR. Quadriceps strength training was limited to open kinematic chain from 90° to 60° of knee flexion for the first 8 weeks after ACLR. Isolated, resisted hamstring strengthening was avoided during this same time frame to protect the hamstring graft site.[2,59] Unilateral, isolated hamstring and quadriceps strengthening was introduced after this time frame as described in the MOON protocol.

Strength Testing

Testing sessions were conducted by testers trained on the assessment protocols. Quadriceps and hamstring strength were quantified with isokinetic dynamometry (Biodex System 3; Biodex Medical Systems), with procedures shown to provide reliable and valid measures of strength after ACL injuries and ACLR.[5,22,55] Concentric isokinetic testing of the quadriceps and hamstring (60 deg/s) was utilized before ACLR and at 12 and 24 weeks after ACLR to record peak torque (N·m). Participants were instructed to actively extend and flex the knee with maximal effort between 10° of knee extension and 100° of knee flexion (Biodex Medical Systems). Participants were given 2 practice repetitions with each test set. Verbal encouragement was provided during practice and test repetitions to ensure participants' best effort. The uninvolved limb was tested first, followed by the involved limb. Two test sets of 5 repetitions of knee extension and flexion at 60 deg/s were performed for each limb, for a total of 4 test sets. The examining clinician monitored participants' comfort and was given the option to stop testing at any time if participants did not feel that they could continue; no participant refused testing because of pain. The highest peak torque values of the 2 sets for knee extension and flexion were used in data analysis. Peak torque was normalized to body weight (kg), and the highest peak torque values from each limb were used to calculate the quadriceps index (QI) and hamstring index (HI) ([*involved limb peak torque/uninvolved limb peak torque*] × 100%).

Self-Reported Outcome Measures

To determine changes in knee function, the Knee injury and Osteoarthritis Outcome Score (KOOS) was completed at all testing time points. The KOOS is a validated outcome measure utilized for athletes after ACLR to document change in multiple areas of perceived function, with higher scores representing higher functional status.[43] The KOOS was administered to assess the patient's perceived functional status on the subscales of Symptoms, Pain, Activities of Daily Living (ADL), Sport/Recreation, and Quality of Life (QOL), with each scored independently (0-100) and 100% equating with perfect function.

Statistical Analysis

Repeated-measures analysis of variance, followed by a post hoc paired *t* test, was used to analyze changes in the QI and HI over time (before ACLR, 12 weeks after ACLR, and 24 weeks after ACLR). Effect sizes were reported as partial eta-square values. The KOOS subscales violated the assumptions of analysis of variance; therefore, the Friedman test, followed by a post hoc Wilcoxon signed-rank test, was used to analyze changes in KOOS subscores over time. Mean differences in KOOS subscores between time points that exceeded published minimal detectable change values were also reported. Spearman rank-order correlations were used to test the relationship between changes in strength and changes in KOOS subscores between adjacent time points (before ACLR to 12 weeks after ACLR and 12 weeks after ACLR to 24 weeks after ACLR). Only participants with complete data sets were used in analysis. Correlation values (r) between 0.25 and 0.50 were considered fair, and values from 0.50 to 0.75 were considered moderate to good.[40]

The sample size was estimated a priori using G*Power 3.1 (http://www.psycho.uni-duesseldorf.de/abteilungen/aap/gpower3/). Based on the previous literature demonstrating significant quadriceps strength gains early in rehabilitation that suggest at least a moderate effect size ($f = 0.5$), power analysis was performed with an alpha level of 0.05 and desired power of 0.90. Based on these data, it was estimated that 11 participants were needed to show a significant change in strength over time. Further power analysis was performed to determine that adequate power would be available for the estimation of Spearman correlations. It was determined that with an alpha level of 0.05 and a moderate correlation ($r = 0.6$), a sample size of 25 would provide sufficient power for this goal of the study (power > 0.90).

TABLE 1
Participant Demographics[a]

Sex, n	
Male	20
Female	10
Age, y	22.2 ± 9.1
Height, m	1.7 ± 0.1
Weight, kg	77.8 ± 15.7
Body mass index, kg/m^2	26.3 ± 4.9
Time from injury to surgery, mo	2.2 ± 3.4
Mechanism of injury, n	
Noncontact	23
Contact	7

[a]Data are expressed as mean ± SD unless otherwise specified.

RESULTS

Demographics

Thirty patients were included in this study (Table 1), and 16 of 30 (53.3%) underwent a meniscal procedure with unilateral ACLR (Table 2). Twenty-three of 30 participants completed all 3 testing sessions (Figure 1).

TABLE 2
Meniscal Procedures

	No. of Participants
No intervention	
No meniscal injury	12
Stable lateral tear without intervention	2
Partial meniscectomy	
Partial medial meniscectomy	3
Partial lateral meniscectomy	9
Meniscal repair	
Medial meniscal repair	1
Meniscal repair with additional procedures	
Medial meniscal repair with partial lateral meniscectomy	1
Lateral meniscal repair with partial lateral meniscectomy	1
Medial/lateral meniscal repair with partial lateral meniscectomy	1

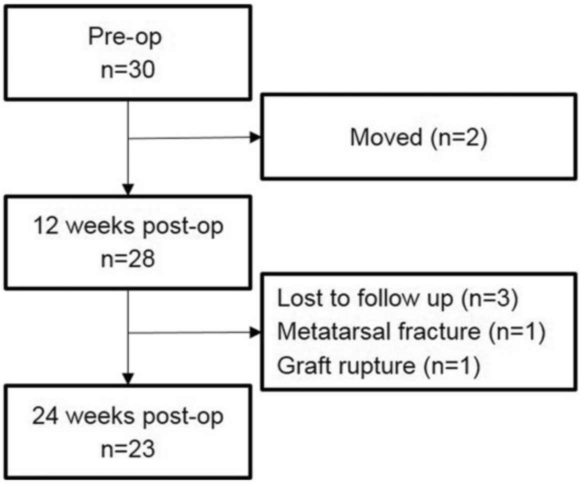

Figure 1. Study flow chart.

Changes in the Quadriceps Index Over Time

There was a statistically significant increase in the QI over time ($F = 3.78$; $P = .030$; partial $\eta^2 = 0.15$) (Table 3). There was no significant change in the QI from before ACLR to 12 weeks after ACLR ($P = .66$), however there was a significant increase in the QI from 12 to 24 weeks after ACLR ($P = .016$).

Changes in the Hamstring Index Over Time

There was a statistically significant increase in the HI over time ($F = 4.01$; $P = .025$; partial $\eta^2 = 0.15$) (Table 3). There was no significant change in the HI from before ACLR to 12 weeks after ACLR ($P = .14$), however there was a significant increase in the HI from 12 to 24 weeks after ACLR ($P < .001$).

Changes in KOOS Values Over Time

Each of the KOOS subscores improved over time ($P < .001$) and between each adjacent time point ($P \leq .02$) (Table 3). Mean subscores demonstrated clinically meaningful difference improvements[45] between before ACLR and 12 weeks after ACLR and again between 12 and 24 weeks after ACLR. Only the KOOS Pain and ADL subscales did not demonstrate a clinically meaningful difference improvement between 12 and 24 weeks postoperatively.

Correlations Between Strength Symmetry and KOOS Values

Changes in the QI were moderately correlated with changes in the KOOS Sport/Recreation subscore ($r = 0.60$), and fair correlations were observed between the QI and the KOOS QOL subscore ($r = 0.39$) from before ACLR to 12 weeks after ACLR ($P \leq .04$) (Figure 2). Changes in the QI were moderately correlated with changes in the KOOS Sport/Recreation subscore only ($r = 0.57$; $P = .005$) from 12 to 24 weeks after ACLR.

Fair correlations were observed between changes in the HI and changes in the KOOS Symptoms subscore from before ACLR to 12 weeks after ACLR ($r = 0.48$; $P \leq .05$) (Figure 3). There were no significant associations between changes in the HI and changes in any of the KOOS subscores from 12 to 24 weeks postoperatively ($P > .05$).

DISCUSSION

The purpose of this study was to determine the relationship between changes in quadriceps and hamstring limb symmetry and self-reported outcomes before ACLR and at 12 and 24 weeks after ACLR. The findings partially confirmed the study hypothesis, in that improvements in quadriceps and hamstring limb symmetry modestly correlated with improvements in self-reported outcomes. Although significant correlations were identified, the strength of those relationships indicates that other factors such as autogenic muscle inhibition, effusion, pain,[38] and psychosocial factors including patient expectations and fear[3] are likely important in improving function early in rehabilitation. Only the QI and KOOS Sport/Recreation subscore demonstrated moderate to good correlation in the early time period after ACLR.

Expectedly, the use of autologous hamstring grafts in ACLR results in hamstring weakness after surgery.[11,23,25] To allow graft site healing and minimize soft tissue irritation, resisted hamstring strengthening is typically avoided in the early postoperative phases of rehabilitation.[59] Hamstring strength improves over time, despite its use as a graft source[13,23,30]; however, there is conflicting evidence regarding the association between the recovery of hamstring strength and improved knee function.[24,26,29,52] Variations in the literature with respect to testing procedures (eg, prone lying vs seated testing), timing of testing, and statistical analyses limit comparisons of outcomes between studies. While the majority of the current literature has

TABLE 3
Mean Quadriceps and Hamstring Indexes and Self-Reported Outcomes[a]

	Before ACLR	12 wk	24 wk	Overall Significance
Strength, %				
Quadriceps symmetry	78.1 (70.7-85.5)	76.7 (69.5-83.9)	83.7 (76.3-91.1)[b]	$F = 3.78$ $P = .030$
Hamstring symmetry	78.9 (72.2-85.6)	71.6 (64.9-78.3)	82.8 (75.5-90.0)[b]	$F = 4.01$ $P = .025$
Function				
KOOS Pain	75.3 (71.2-79.4)	89.0 (85.1-92.9)[c,d]	92.3 (88.9-95.7)[b]	$\chi^2 = 31.7$ $P < .001$
KOOS Symptoms	68.0 (63.6-72.3)	78.4 (71.0-85.8)[c,d]	89.6 (85.8-93.4)[b,d]	$\chi^2 = 30.5$ $P < .001$
KOOS ADL	88.3 (84.8-91.8)	96.9 (93.6-100.2)[c,d]	99.0 (98.1-99.9)[b]	$\chi^2 = 34.4$ $P < .001$
KOOS Sport/Recreation	50.4 (42.6-58.2)	73.2 (66.1-80.2)[c,d]	83.0 (74.7-91.3)[b,d]	$\chi^2 = 30.6$ $P < .001$
KOOS QOL	44.6 (38.0-51.2)	58.3 (51.2-65.4)[c,d]	67.9 (59.0-76.8)[d]	$\chi^2 = 29.3$ $P < .001$

[a]Data are expressed as mean (95% CI). ACLR, anterior cruciate ligament reconstruction; ADL, Activities of Daily Living; KOOS, Knee injury and Osteoarthritis Outcome Score; QOL, Quality of Life.
[b]Significant difference ($P < .05$) relative to 12-week value.
[c]Significant difference ($P < .05$) relative to value before ACLR.
[d]Clinically meaningful improvement.

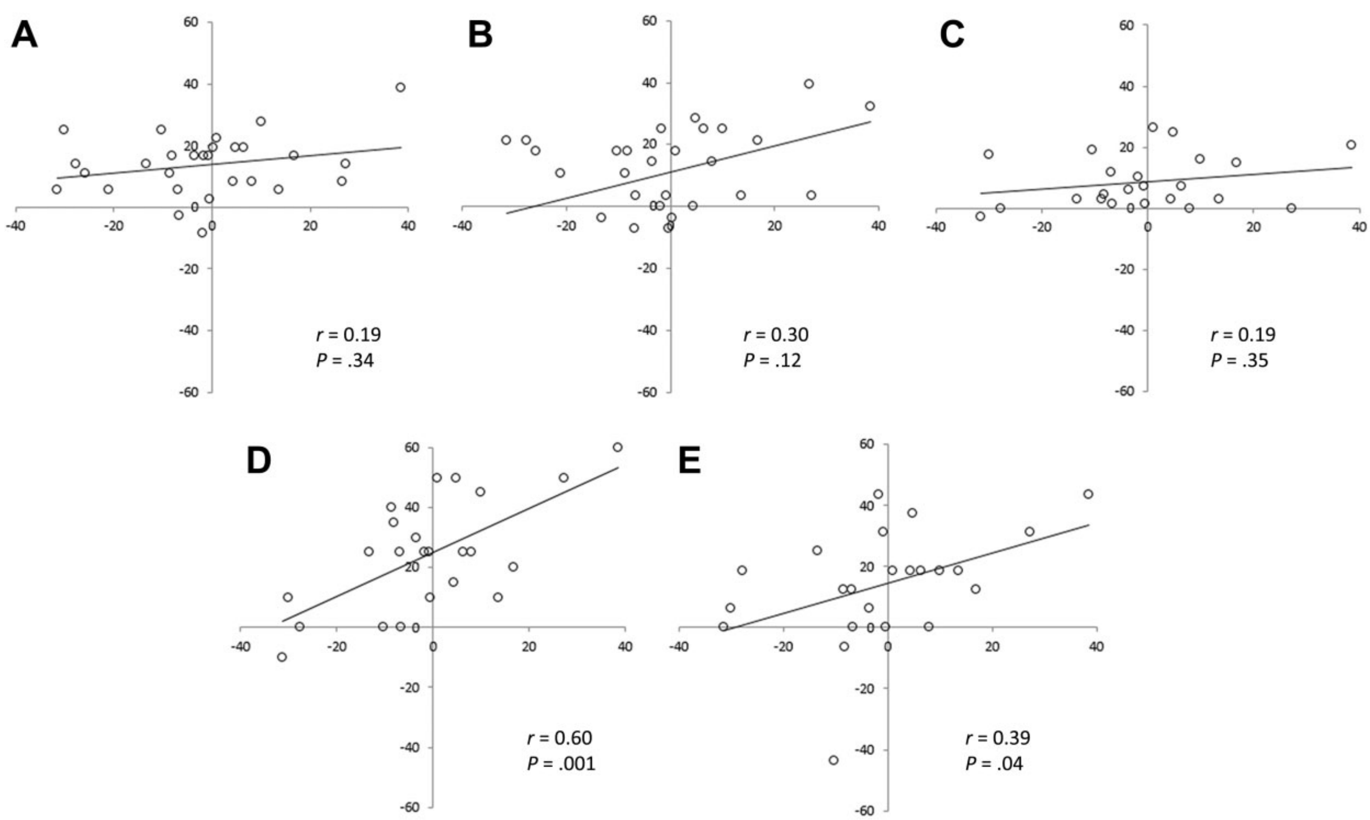

Figure 2. Scatter plots of changes in the quadriceps index (QI) and Knee injury and Osteoarthritis Outcome Score (KOOS) subscales of (A) Pain, (B) Symptoms, (C) Activities of Daily Living, (D) Sport/Recreation, and (E) Quality of Life from before anterior cruciate ligament reconstruction (ACLR) to 12 weeks after ACLR. Negative x-axis values indicate a decline in strength symmetry; negative y-axis values indicate a decline in the KOOS score.

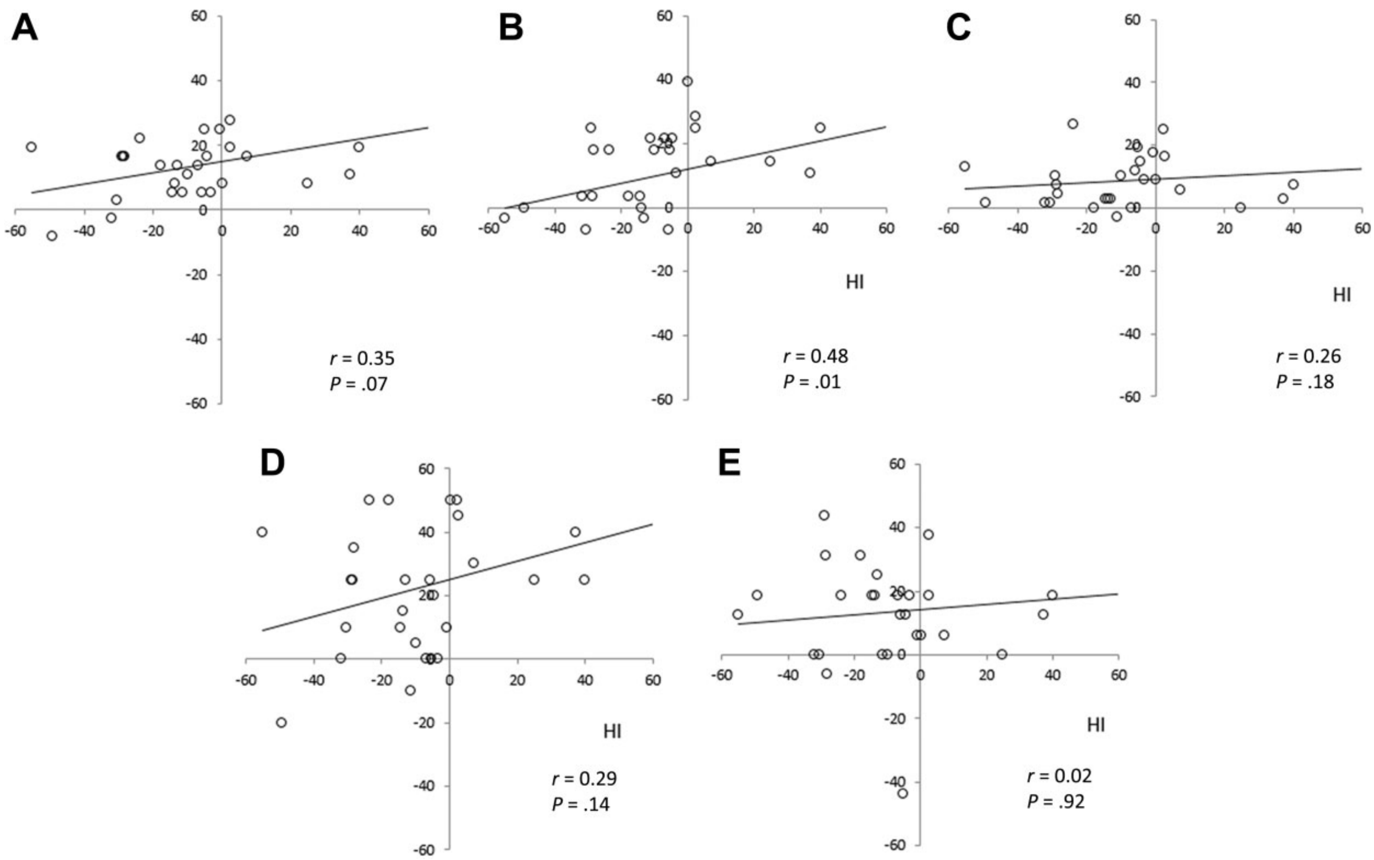

Figure 3. Scatter plots of changes in the hamstring index (HI) and Knee injury and Osteoarthritis Outcome Score (KOOS) subscales of (A) Pain, (B) Symptoms, (C) Activities of Daily Living, (D) Sport/Recreation, and (E) Quality of Life from before anterior cruciate ligament reconstruction (ACLR) to 12 weeks after ACLR. Negative x-axis values indicate a decline in strength symmetry; negative y-axis values indicate a decline in the KOOS score.

focused on the long-term recovery of hamstring strength and function,[19,26,29,52] the present study, to our knowledge, is the only study that evaluates these relationships within the first 6 months after ACLR. Fair correlations between improvements in the HI and the KOOS Symptoms subscore were noted within the first 12 weeks postoperatively. As isolated, resisted hamstring strengthening was not initiated in this cohort before 8 weeks after ACLR, the relationship may be partly attributed to a reduction in postoperative inflammation and effusion.

Quadriceps weakness is common after ACLR, regardless of the graft choice.[11] Importantly, the restoration of quadriceps strength and sport-related knee function after ACLR varies greatly.[7,11,22,27,35,41] Despite a well-established positive relationship between quadriceps strength and knee function,[24,31,46,53] there is little known about this relationship in the early phases of recovery after ACLR. Data from the present study demonstrated a moderate, positive correlation between changes in the QI and the KOOS Sport/Recreation subscore between preoperatively and 12 weeks postoperatively and between 12 and 24 weeks postoperatively. Fair correlations between improvements in the QI and the KOOS QOL subscore were also observed within the first 12 weeks after ACLR.

To our knowledge, only 1 other study has evaluated lower extremity strength and function during the early recovery phase after ACLR. In a retrospective study of 63 patients who had undergone ACLR and a standard postoperative rehabilitation protocol, Christensen et al[9] showed that higher peak isometric force symmetry measured via a unilateral leg press at 4 and 8 weeks after ACLR explained approximately 30% of the variance in self-reported knee function at each respective time point. Their data indicate a similar positive relationship between strength symmetry and self-reported function as identified in the present prospective investigation.

Athletes typically progress to high-impact, sport-related activities such as running and jumping between 12 and 24 weeks after surgery.[2,8,34] The current study demonstrated a moderate to good association between improvements in the QI and the KOOS Sport/Recreation subscore during this time frame. These data are consistent with other long-term data demonstrating that higher quadriceps symmetry is related to better performance during dynamic tasks such as single-leg hopping.[46] In isolation, patient-reported outcomes cannot fully capture impairments that contribute to functional limitations in this population. The literature suggests that other factors such as autogenic muscle inhibition, effusion, pain,[38] and patient expectations and fear[3] likely play a role in knee function as well. However, frequent and early testing of quadriceps strength, in combination with patient-reported outcome measures, may help rehabilitation specialists progress athletes to high-impact activities appropriately and avoid undue stress and loading to the knee joint. These findings highlight the important relationship between gains in quadriceps strength and sport-related knee function within the first several weeks and months after ACLR and may help clinicians identify the impairments early and tailor therapeutic exercises to prevent delayed recovery and potentially improve return-to-sport metrics.

Limitations

The participant attrition rate was 24%, which is higher than the commonly acceptable 20% cutoff for clinical trials, which may have underpowered the analysis. Limb symmetry indexes were used to maintain consistency with return-to-sport guidelines in the ACLR population. However, we acknowledge that limb symmetry may not be the best representation of strength changes, as it can mask the independent changes in muscle strength between involved and uninvolved limbs.[19,50] Patient positioning for hamstring isokinetic strength testing is controversial in the literature,[51,57,58] and testing hamstring strength in a seated position may not capture strength deficits in deep knee flexion angles, which is a position that has been associated with knee function.[16,20] No participant refused strength testing because of pain, but the presence of pain could have influenced force production. These data are limited to acutely injured athletes who undergo ACLR with hamstring autografts; thus, the findings cannot be extrapolated to populations with other graft types.

CONCLUSION

In the first 6 months after ACLR using hamstring autografts, changes in hamstring and quadriceps symmetry were positively associated with changes in the KOOS Symptoms subscore and the KOOS Sport/Recreation and QOL subscores, respectively. Correlations were only fair to moderate. Additional studies that explore strength changes among the multifactorial contributions to improvements in patient-reported function are necessary to inform best practices in rehabilitation after ACLR.

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REFERENCES

1. Abourezk MN, Ithurburn MP, McNally MP, et al. Hamstring strength asymmetry at 3 years after anterior cruciate ligament reconstruction alters knee mechanics during gait and jogging. *Am J Sports Med*. 2017;45(1):97-105.
2. Adams D, Logerstedt D, Hunter-Giordano A, Axe MJ, Snyder-Mackler L. Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. *J Orthop Sports Phys Ther*. 2012;42(7):601-614.
3. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE. Psychological responses matter in returning to preinjury level of sport after anterior cruciate ligament reconstruction surgery. *Am J Sports Med*. 2013;41(7):1549-1558.
4. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br J Sports Med*. 2011;45(7): 596-606.
5. Brosky JA, Nitz AJ, Malone TR, Caborn DNM, Rayens MK. Intrarater reliability of selected clinical outcome measures following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 1999; 29(1):39-48.
6. Bryant AL, Creaby MW, Newton RU, Steele JR. Dynamic restraint capacity of the hamstring muscles has important functional implications after anterior cruciate ligament injury and anterior cruciate ligament reconstruction. *Arch Phys Med Rehabil*. 2008;89(12):2324-2331.
7. Bush-Joseph CA, Hurwitz DE, Patel RR, et al. Dynamic function after anterior cruciate ligament reconstruction with autologous patellar tendon. *Am J Sports Med*. 2001;29(1):36-41.
8. Cascio BM, Culp L, Cosgarea AJ. Return to play after anterior cruciate ligament reconstruction. *Clin Sports Med*. 2004;23(3):395-408.
9. Christensen JC, Goldfine LR, Barker T, Collingridge DS. What can the first 2 months tell us about outcomes after anterior cruciate ligament reconstruction? *J Athl Train*. 2015;50(5):508-515.
10. Daniel DM, Fithian DC. Indications for ACL surgery. *Arthroscopy*. 1994;10(4):434-441.
11. de Jong SN, van Caspel DR, van Haeff MJ, Saris DBF. Functional assessment and muscle strength before and after reconstruction of chronic anterior cruciate ligament lesions. *Arthroscopy*. 2007;23(1):21-28.
12. Eitzen I, Holm I, Risberg MA. Preoperative quadriceps strength is a significant predictor of knee function two years after anterior cruciate ligament reconstruction. *Br J Sports Med*. 2009;43(5):371-376.
13. Emami Meybodi MK, Jannesari M, Rahim Nia A, Yaribeygi H, Firoozabad VS, Dorostegan A. Knee flexion strength before and after ACL reconstruction using hamstring tendon autografts. *Trauma Mon*. 2013;18(3):130-133.
14. Eriksson E. Hamstring tendons or patellar tendon as graft for ACL reconstruction? *Knee Surg Sports Traumatol Arthrosc*. 2007;15(2):113-114.
15. Georgoulis A, Tsepis E, Vagenas G, Giakas G. Hamstring weakness as an indicator of poor knee function in ACL-deficient patients. *Knee Surg Sports Traumatol Arthrosc*. 2004;12(1):22-29.
16. Guex K, Gojanovic B, Millet GP. Influence of hip-flexion angle on hamstrings isokinetic activity in sprinters. *J Athl Train*. 2012;47(4):390-395.
17. Hartigan E, Axe MJ, Snyder-Mackler L. Perturbation training prior to ACL reconstruction improves gait asymmetries in non-copers. *J Orthop Res*. 2009;27(6):724-729.
18. Hefti F, Müller W, Jakob RP, Stäubli HU. Evaluation of knee ligament injuries with the IKDC form. *Knee Surg Sports Traumatol Arthrosc*. 1993;1(3-4):226-234.
19. Hiemstra LA, Webber S, MacDonald PB, Kriellaars DJ. Contralateral limb strength deficits after anterior cruciate ligament reconstruction using a hamstring tendon graft. *Clin Biomech (Bristol, Avon)*. 2007; 22(5):543-550.
20. Irrgang JJ, Delitto A, Hagen B, Huber F, Pezzullo D. Rehabilitation of the injured athlete. *Orthop Clin North Am*. 1995;26(3):561-577.
21. Ithurburn MP, Altenburger AR, Thomas S, Hewett TE, Paterno MV, Schmitt LC. Young athletes after ACL reconstruction with quadriceps strength asymmetry at the time of return-to-sport demonstrate decreased knee function 1 year later. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(2):426-433.
22. Järvelä T, Kannus P, Latvala K, Järvinen M. Simple measurements in assessing muscle performance after an ACL reconstruction. *Int J Sports Med*. 2002;23(3):196-201.

23. Karanikas K, Arampatzis A, Brüggemann GP. Motor task and muscle strength followed different adaptation patterns after anterior cruciate ligament reconstruction. *Eur J Phys Rehabil Med*. 2009;45(1):37-45.
24. Keays SL, Bullock-Saxton JE, Newcombe P, Keays AC. The relationship between knee strength and functional stability before and after anterior cruciate ligament reconstruction. *J Orthop Res*. 2003;21(2): 231-237.
25. Kim JG, Yang SJ, Lee YS, Shim JC, Ra HJ, Choi JY. The effects of hamstring harvesting on outcomes in anterior cruciate ligament–reconstructed patients: a comparative study between hamstring-harvested and -unharvested patients. *Arthroscopy*. 2011;27(9): 1226-1234.
26. Ko MS, Yang SJ, Ha JK, et al. Correlation between hamstring flexor power restoration and functional performance test: 2-year follow-up after ACL reconstruction using hamstring autograft. *Knee Surg Relat Res*. 2012;24(2):113-119.
27. Kobayashi Y, Kubo J, Matsubayashi T, Matsuo A, Kobayashi K, Ishii N. Relationship between bilateral differences in single-leg jumps and asymmetry in isokinetic knee strength. *J Appl Biomech*. 2013;29(1): 61-67.
28. Kruse LM, Gray B, Wright RW. Rehabilitation after anterior cruciate ligament reconstruction: a systematic review. *J Bone Joint Surg Am*. 2012;94(19):1737-1748.
29. Lautamies R, Harilainen A, Kettunen J, Sandelin J, Kujala UM. Isokinetic quadriceps and hamstring muscle strength and knee function 5 years after anterior cruciate ligament reconstruction: comparison between bone-patellar tendon-bone and hamstring tendon autografts. *Knee Surg Sports Traumatol Arthrosc*. 2008;16(11):1009-1016.
30. Lee D-H, Lee J-H, Jeong H-J, Lee S-J. Serial changes in knee muscle strength after anterior cruciate ligament reconstruction using hamstring tendon autografts. *Arthroscopy*. 2015;31(5):890-895.
31. Lewek M, Rudolph K, Axe M, Snyder-Mackler L. The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. *Clin Biomech (Bristol, Avon)*. 2002;17(1):56-63.
32. Logerstedt D, Lynch A, Axe MJ, Snyder-Mackler L. Pre-operative quadriceps strength predicts IKDC2000 scores 6 months after anterior cruciate ligament reconstruction. *Knee*. 2013;20(3):208-212.
33. Magnussen R, Pottkotter K, Stasi S, et al. Femoral nerve block after anterior cruciate ligament reconstruction. *J Knee Surg*. 2016;30(4): 323-328.
34. Marx RG, Jones EC, Angel M, Wickiewicz TL, Warren RF. Beliefs and attitudes of members of the American Academy of Orthopaedic Surgeons regarding the treatment of anterior cruciate ligament injury. *Arthroscopy*. 2003;19(7):762-770.
35. Mattacola CG, Perrin DH, Gansneder BM, et al. Strength, functional outcome, and postural stability after anterior cruciate ligament reconstruction. *J Athl Train*. 2002;37(3):262-268.
36. McRae SM, Chahal J, Leiter JR, Marx RG, Macdonald PB. Survey study of members of the Canadian Orthopaedic Association on the natural history and treatment of anterior cruciate ligament injury. *Clin J Sport Med*. 2011;21(3):249-258.
37. Nakayama Y, Shirai Y, Narita T, Mori A, Kobayashi K. Knee functions and a return to sports activity in competitive athletes following anterior cruciate ligament reconstruction. *J Nippon Med Sch*. 2000;67(3): 172-176.
38. Palmieri-Smith RM, Thomas AC, Wojtys EM. Maximizing quadriceps strength after ACL reconstruction. *Clin Sports Med*. 2008;27(3): 405-424.
39. Peterson L, Eklund U, Engström B, Forssblad M, Saartok T, Valentin A. Long-term results of a randomized study on anterior cruciate ligament reconstruction with or without a synthetic degradable augmentation device to support the autograft. *Knee Surg Sports Traumatol Arthrosc*. 2014;22(9):2109-2120.
40. Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Practice*. 3rd ed. Philadelphia: FA Davis Company; 2015.
41. Risberg MA, Holm I. The long-term effect of 2 postoperative rehabilitation programs after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2009;37(10):1958-1966.
42. Robertson GA, Coleman SG, Keating JF. The surgical treatment of knee stiffness following anterior cruciate ligament reconstruction. *Scott Med J*. 2011;56(3):156-160.
43. Roos EM, Roos HP, Lohmander LS, Ekdahl C, Beynnon BD. Knee injury and Osteoarthritis Outcome Score (KOOS): development of a self-administered outcome measure. *J Orthop Sports Phys Ther*. 1998;28(2):88-96.
44. Rudolph KS, Eastlack ME, Axe MJ, Snyder-Mackler L. 1998 Basmajian Student Award Paper. Movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. *J Electromyogr Kinesiol*. 1998;8(6):349-362.
45. Salavati M, Akhbari B, Mohammadi F, Mazaheri M, Khorrami M. Knee injury and Osteoarthritis Outcome Score (KOOS): reliability and validity in competitive athletes after anterior cruciate ligament reconstruction. *Osteoarthritis Cartilage*. 2011;19(4):406-410.
46. Schmitt LC, Paterno MV, Hewett TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2012;42(9):750-759.
47. Shelbourne KD, Patel DV. Treatment of limited motion after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 1999;7(2):85-92.
48. Smith FW, Rosenlund EA, Aune AK, MacLean JA, Hillis SW. Subjective functional assessments and the return to competitive sport after anterior cruciate ligament reconstruction. *Br J Sports Med*. 2004; 38(3):279-284.
49. Snyder-Mackler L, Ladin Z, Schepsis AA, Young JC. Electrical stimulation of the thigh muscles after reconstruction of the anterior cruciate ligament: effects of electrically elicited contraction of the quadriceps femoris and hamstring muscles on gait and on strength of the thigh muscles. *J Bone Joint Surg Am*. 1991;73(7):1025-1036.
50. Urbach D, Awiszus F. Impaired ability of voluntary quadriceps activation bilaterally interferes with function testing after knee injuries: a twitch interpolation study. *Int J Sports Med*. 2002;23(4):231-236.
51. Vairo GL. Knee flexor strength and endurance profiles after ipsilateral hamstring tendons anterior cruciate ligament reconstruction. *Arch Phys Med Rehabil*. 2014;95(3):552-561.
52. Villa FD, Ricci M, Perdisa F, et al. Anterior cruciate ligament reconstruction and rehabilitation: predictors of functional outcome. *Joints*. 2015;3(4):179-185.
53. Ward SH, Blackburn JT, Padua DA, et al. Quadriceps neuromuscular function and jump-landing sagittal-plane knee biomechanics after anterior cruciate ligament reconstruction. *J Athl Train*. 2018;53(2): 135-143.
54. Wild CY, Steele JR, Munro BJ. Insufficient hamstring strength compromises landing technique in adolescent girls. *Med Sci Sports Exerc*. 2013;45(3):497-505.
55. Wilk KE, Romaniello WT, Soscia SM, Arrigo CA, Andrews JR. The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. *J Orthop Sports Phys Ther*. 1994;20(2):60-73.
56. Williams GN, Snyder-Mackler L, Barrance PJ, Axe MJ, Buchanan TS. Neuromuscular function after anterior cruciate ligament reconstruction with autologous semitendinosus-gracilis graft. *J Electromyogr Kinesiol*. 2005;15(2):170-180.
57. Worrell TW, Denegar CR, Armstrong SL, Perrin DH. Effect of body position on hamstring muscle group average torque. *J Orthop Sports Phys Ther*. 1990;11(10):449-452.
58. Worrell TW, Perrin DH, Denegar CR. The influence of hip position on quadriceps and hamstring peak torque and reciprocal muscle group ratio values. *J Orthop Sports Phys Ther*. 1989;11(3):104-107.
59. Wright RW, Haas AK, Anderson J, et al. Anterior cruciate ligament reconstruction rehabilitation: MOON guidelines. *Sports Health*. 2015; 7(3):239-243.
60. Wright RW, Preston E, Fleming BC, et al. A systematic review of anterior cruciate ligament reconstruction rehabilitation, part I: continuous passive motion, early weight bearing, postoperative bracing, and home-based rehabilitation. *J Knee Surg*. 2008;21(3):217-224.