Hip Strength Recovery After Anterior Cruciate Ligament Reconstruction

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Background: Return-to-play (RTP) assessment after anterior cruciate ligament reconstruction (ACLR) rarely includes hip strength.

Hypothesis: It was hypothesized that (1) patients after ACLR will have weaker hip abduction (AB) and adduction (AD) strength compared with the contralateral limb, with larger deficits in women, (2) there will be a correlation between hip and thigh strength ratios and patient-reported outcomes (PROs), and (3) hip AB and AD strength will improve over time.

Study Design: Descriptive laboratory study.

Methods: Included were 140 patients (74 male, 66 female; mean age, 24.16 ± 10.82 years) who underwent RTP assessment at 6.1 ± 1.6 months after ACLR; 86 patients underwent a second assessment at 8.2 ± 2.2 months. Hip AB/AD and knee extension/flexion isometric strength were measured and normalized to body mass, and PRO scores were collected. Strength ratios (hip vs thigh), limb differences (injured vs uninjured), sex-based differences, and relationships between strength ratios and PROs were determined.

Results: Hip AB strength was weaker on the ACLR limb (ACLR vs contralateral: 1.85 ± 0.49 vs 1.89 ± 0.48 N·m/kg; $P < .001$) and hip AD torque was stronger (ACLR vs contralateral: 1.80 ± 0.51 vs 1.76 ± 0.52 N·m/kg; $P = .004$), with no sex-by-limb interaction found. Lower hip-to-thigh strength ratios of the ACLR limb were correlated with higher PRO scores ($r = -0.17$ to -0.25). Over time, hip AB strength increased in the ACLR limb more than in the contralateral limb ($P = .01$); however, the ACLR limb remained weaker in hip AB at visit 2 (ACLR vs contralateral: 1.88 ± 0.46 vs 1.91 ± 0.45 N·m/kg; $P = .04$). In both limbs, hip AD strength was greater at visit 2 than visit 1 (ACLR: 1.82 ± 0.48 vs 1.70 ± 0.48 N·m/kg; contralateral: 1.76 ± 0.47 vs 1.67 ± 0.47 N·m/kg; $P < .01$ for both).

Conclusion: The ACLR limb had weaker hip AB and stronger AD compared with the contralateral limb at initial assessment. Hip muscle strength recovery was not influenced by sex. Hip strength and symmetry improved over the course of rehabilitation. Although strength differences across limbs were minor, the clinical importance of these differences is still unknown.

Clinical Relevance: The evidence provided highlights the need to integrate hip strength into RTP assessments to identify hip strength deficits that may increase reinjury or lead to poor long-term outcomes.

Keywords: muscle recovery; return to play; strength testing; injury

Anterior cruciate ligament (ACL) injury is a common musculoskeletal injury in active populations.[16] After an ACL injury individuals often opt for surgical reconstruction (ACL reconstruction [ACLR]).[16,17] Patients who undergo ACLR commonly complete supervised rehabilitation in order to return to play (RTP); however, despite these efforts only 50% to 55% of individuals will return to their previous competitive level of sport, 80% to 81% will return to recreational activities, and approximately 23% to 30% of individuals will experience a reinjury to either the reconstructed or the contralateral limb.[2,5,18,35]

Many clinicians encourage their patients to participate in a series of assessments and questionnaires to gauge

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their progression during rehabilitation and to determine their readiness for release from care and return to unrestricted physical activity.[35,46] These tests typically include objective measures of strength and function as well as patient-reported outcomes (PROs).[16] These tests can guide clinicians' decisions on whether a patient is ready to return to preinjury levels of physical activity or whether additional rehabilitation sessions are warranted.[35,46] Persistent lower extremity muscle weakness has been repeatedly observed in the quadriceps and hamstring musculature; as a result, traditional rehabilitation primarily focuses on strengthening these 2 muscle groups after ACLR.[1,3,13,18,27,30,31] Previous studies have examined the influence that hip adduction (AD) and abduction (AB) strength have on ACL injury occurrence[4,12,24] and found that hip strength deficits may be associated with risky biomechanical movement such as increased knee valgus moments, valgus positioning, and a loss of frontal plane postural stability.[6,9,28] These changes in biomechanical movement patterns have been reported as risk factors for initial ACL injury and reinjury.[22,36] Additionally, a recent study indicated sex differences during a landing task, where women had significantly lower hip AB peak torque when normalized to body weight.[25] Hip weakness in women has been indicated as a risk factor for future noncontact ACL injuries and patellofemoral pain.[25,28] Hip strengthening has not been a typical component of RTP assessment used to track rehabilitation progress and outcomes after ACLR.[21]

The utility of muscle strength ratios, specifically the hamstring-to-quadriceps strength ratio, as risk factor indicators of lower extremity injury has been previously explored[46]; however, there have been mixed findings.[27,46] One study found lower hamstring-to-quadriceps strength ratios are indicative of lower limb strength imbalances and are potential risk factors for ACL graft rupture.[30] Another study discussed a lack of association between hamstring-to-quadriceps strength ratios and lower extremity injury.[27] More recently, investigators have begun examining the influence of a hip abductor strength ratio on altered jump landing mechanics.[21] However, it is unclear how lower extremity strength ratios might relate to subjective outcomes after ACLR.

The 3 aims of this study were to (1) compare hip AB and AD strength between the reconstructed and contralateral limb and between men and women recovering from ACLR, (2) examine the relationship between hip and thigh strength ratios and PROs, and (3) determine whether hip AB and AD strength changed from early to late phase rehabilitation after ACLR. We hypothesized that (1) participants would have weaker hip AB and AD strength compared with the contralateral limb and that this strength deficit would be larger in women compared with their male counterparts, (2) there would be a relationship between hip and thigh strength ratios and PROs, and (3) hip strength from both the AB and AD musculature would improve across RTP assessment visits.

METHODS

Study Design

The study protocol was approved by the university's institutional review board for health sciences research. This was an observational cohort study conducted in a controlled laboratory setting as part of a larger point-of-care, collaborative research program within an academic health system. Patients attended objective and subjective testing during a visit to our university laboratory before their RTP time point, approximately 5 to 10 months after surgery (visit 1). The patients were also given the option to attend an early testing visit around 4 months after surgery, with data provided to track their improvement over time. A subset of the study patients returned for a second assessment (visit 2), during which all testing procedures were repeated.

The sample size estimate was based on identifying sex differences in hip AB strength using data collected in our laboratory as a variability estimate in hip AB torque. We determined that ≥63 patients per group were necessary to identify a moderate effect size (0.5) between sexes at an alpha level of .05 and an error rate of 0.8.

Participants

A total of 327 patients were referred to our laboratory from their orthopaedic surgeon within our academic health

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Ethical approval for this study was obtained from the University of Virginia (reference No. 17399).

TABLE 1
Participant Characteristics[a]

	Patients Who Completed Only Visit 1 (n = 54)	Patients Who Completed Visits 1 and 2 (n = 86)	All Patients (n = 140)
Sex, male/female, n	35/19	39/47	74/66
Age, y	25.69 ± 11.92	22.93 ± 9.85	24.16 ± 10.82
Mass, kg	80.51 ± 19.73	77.43 ± 18.05	79.46 ± 19.18
Height, cm	172.96 ± 11.43	172.17 ± 10.19	172.79 ± 10.64
Follow-up time, mo	Visit 1: 6.05 ± 1.54	Visit 1: 4.86 ± 1.54 Visit 2: 8.24 ± 2.23	Visit 1: 6.13 ± 1.57
Graft type			
Patellar tendon	36 (66.67)	72 (83.7)	108 (77.1)
Hamstring tendon	16 (29.63)	12 (14)	28 (20.0)
Quadriceps tendon	1 (1.85)	2 (2.3)	3 (2.1)
Allograft	1 (1.85)	0 (0)	1 (0.7)

[a]Data are reported as mean ± SD or n (%) unless otherwise indicated.

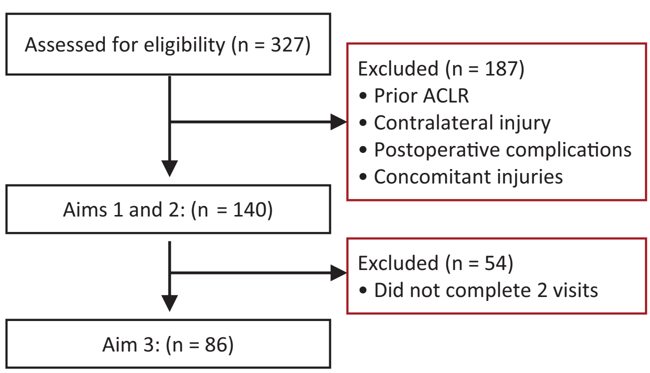

Figure 1. Patients who underwent anterior cruciate ligament reconstruction (ACLR) and were screened and enrolled for the 3 aims of this study.

system. The patients were given a suggested standard-of-care rehabilitation protocol from their orthopaedic surgeon; however, they underwent rehabilitation in various clinic locations based on patient preference and convenience. The inclusion criterion for this study was primary, unilateral, uncomplicated, and isolated ACLR surgery. Patients were excluded if they had undergone a prior ACLR surgery, multiligament reconstruction, graft failure, or contralateral ACL injury; if they had any other lower extremity injury or concussion within the past 6 months; or if they had any neurological disorders. A total of 140 patients were considered eligible and provided written informed consent before enrollment. Of these patients, 86 attended visit 2. The enrollment procedure is shown in Figure 1, and participant characteristics are shown in Table 1.

Procedures

Strength evaluations at both time points were performed during a single session where hip muscle strength, knee muscle strength, and PROs were measured by 3 trained investigators (A.S.B.L., X.D.T., H.M.H.). Patients underwent a standardized warm-up protocol on a treadmill before all testing procedures. The warm-up protocol was a 5-minute walk on a treadmill (Gait Trainer 3; Biodex Medical Systems Inc) at a standardized pace of 3 mph.

Hip Strength Measurement

Hip AB and AD peak torques were measured bilaterally during maximal voluntary isometric contractions (MVICs) for each patient using a force dynamometer (ForceFrame; Vald Performance) sampled at 50 Hz, which has been previously reported to be reliable with coefficient of variation values <10%.[10,42] Participants were instructed to lie supine with their knees and hips flexed to 45° (Figure 2). All participants performed three 5-second maximal isometric hip AD and AB contraction trials. All data were averaged across the 3 trials. Participants performed AD MVICs bilaterally first, followed by AB MVICs, with 30-second rest given between sets.

Knee Strength Measurement

Isometric quadriceps and hamstring peak torques were measured bilaterally during knee extension and flexion during an MVIC using a multimodal dynamometer (Systems IV; Biodex Medical Systems Inc) using a universal data export to a data acquisition system (MP150; Biopac Inc) sampled at 125 Hz and low-pass filtered at 15 Hz for data processing. Patients were seated in the dynamometer chair with their hips flexed at 85° and knees flexed at 90°, and were instructed to either kick their knee out to evaluate quadriceps strength or pull back for hamstring strength "as hard as possible" for a maximal 30-second effort (Figure 3).[11] The contralateral limb was always tested first, and then the test was repeated for the ACLR limb.

Patient-Reported Outcomes

All participants completed a series of PROs during the visit. The International Knee Documentation Committee

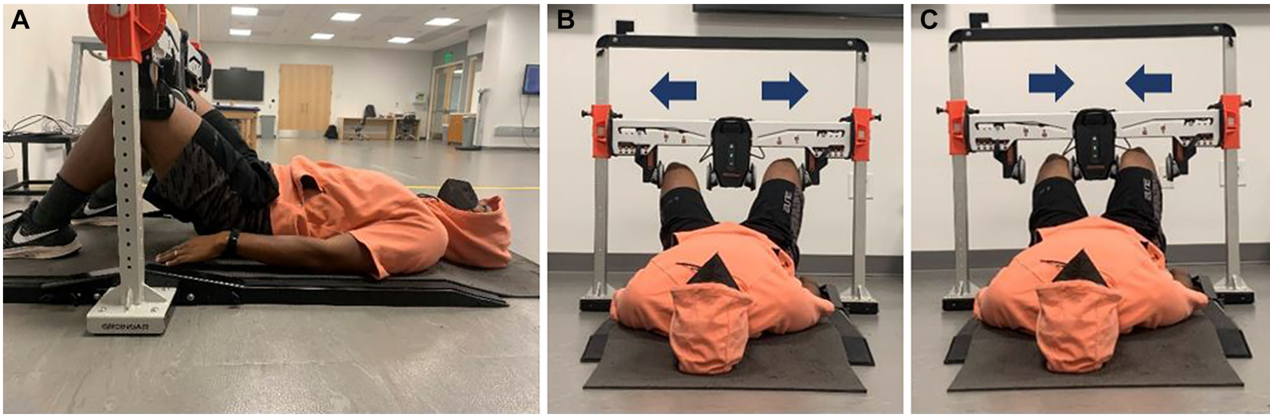

Figure 2. (A) Setup for hip strength testing. (B) Hip abduction testing position. (C) Hip adduction testing position.

(IKDC) Subjective Knee Form was collected to determine subjective knee function.[23] The Knee injury and Osteoarthritis Outcome Score (KOOS) was used to evaluate the severity of the knee symptoms and functional disabilities.[41] Last, the Anterior Cruciate Ligament–Return to Sport after Injury (ACL-RSI) score was collected to assess patient emotions, confidence, and risk appraisal in relation to resuming sport-related activities.[45]

Data Processing

Hip torque was calculated using force obtained from the isometric dynamometer (newtons) multiplied by femoral length (meters) derived from patient height using previously reported sex-specific equations[44] and was normalized to body mass (N·m/kg). The peak torque MVIC for thigh muscle torque was calculated by obtaining the maximal 1-second average from the first 5 seconds of the test.[11] Limb strength was reported as the limb symmetry index (LSI; in percentage) between the ACLR and contralateral limb, calculated as (*ACLR limb/contralateral limb*) × 100.[3] Lower extremity strength ratios were calculated from non-normalized torque values. The following lower extremity strength ratios were calculated: hamstring to quadriceps (H/Q), AB to AD (AB/AD), AB to quadriceps (AB/Q), AD to quadriceps (AD/Q), AB to hamstring (AB/H), and AD to hamstring (AD/H). These ratios were categorized into either an agonist-to-antagonist ratio group (H/Q and AB/AD) or a hip-to-thigh ratio group (AB/Q, AD/Q, AB/H, and AD/H).

Statistical Analysis

The independent variables were limb (ACLR vs contralateral), sex (male vs female), and time (visit 1 vs visit 2). The dependent variables were bilateral hip AB, hip AD, knee extension and knee flexion strength (peak torque normalized to body mass), and PROs (IKDC, KOOS, and ACL-RSI). LSIs and strength ratios were compared across the hip AB and AD musculature as well as within the quadriceps and hamstring muscle groups.

Figure 3. Setup for the knee strength assessment.

For aim 1, a separate 2 × 2 (limb-by-sex) repeated-measures analysis of variance (ANOVA) was used to compare hip strength between men and women. Post hoc t tests were performed as appropriate. A paired-samples t test was used to compare hip AB and AD limb symmetry between the men and women and between the ACLR and contralateral limbs for individuals with a single visit. The Cohen effect size (d) was calculated and used to interpret pooled standardized mean differences, which represent the magnitude of observed differences.[29,34] Effect size values were classified as weak ($\leq$0.2), small (0.2-0.49), moderate (0.5-0.8), or large ($\geq$0.8).[29]

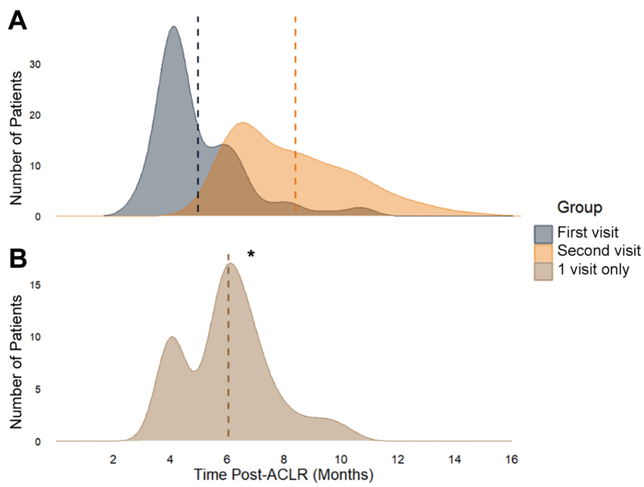

Figure 4. Distribution of time post–anterior cruciate ligament reconstruction (ACLR) in months for patients who attended 2 visits compared with attending a singular visit. Dashed vertical lines indicate the mean time post-ACLR for (A) individuals at their first and second visits and (B) those who attended 1 visit only. *Patients who only attended 1 visit were evaluated significantly later than the first visit of those who attended 2 serial visits ($P < .001$).

For aim 2, the Pearson correlation coefficient (r) was used to determine the association between PRO scores and hip and thigh muscle strength ratios. Correlation coefficients were classified as weak (0.0-0.25), fair (0.26-0.50), moderate (0.51-0.75), or strong ($\geq$0.76).[34]

For aim 3, we used 2 × 2 (limb-by-time) repeated-measures ANOVA to compare hip strength between visits 1 and 2. Post hoc t tests were performed as appropriate. A paired-samples t test was used to compare hip AB and AD limb symmetry between visits 1 and 2.

SPSS Version 28 (IBM Corp) was used for all statistical calculations, and the α level was set α priori at ≤.05 for all analyses.

RESULTS

There was a statistically significant difference in time post-surgery between the participants who completed 1 visit (n = 140) compared with participants who completed 2 visits (n = 86), in which patients who attended only 1 visit were evaluated significantly later than the first visit of patients who attended 2 serial visits (time postoperatively: 6.05 ± 1.54 vs 4.86 ± 1.54 months, respectively; t = 4.46; $P < .001$; d = 0.77) (Figure 4).

There were no significant limb-by-sex interactions for hip AB ($F_{(1,138)} = 0.01$; $P = .92$) or hip AD ($F_{(1,138)} = 0.03$; $P = .86$) strength. There was a main effect for sex, where men had greater hip AB and AD strength values than women (AB: $F_{(1,138)} = 12.01$, $P < .01$, $d = 0.88$; AD: $F_{(1,138)} = 7.31$, $P = .008$, $d = 0.61$) (Table 2). There was also a main effect for the limb for both hip AB and AD normalized peak torques. The hip AB torque of the ACLR limb

TABLE 2
Hip Strength Across Limbs and Between Sexes at Visit 1 (n = 140)[a]

	Hip AB Strength		Hip AD Strength	
Variable	ACLR	Contralateral	ACLR	Contralateral
Overall	1.85 ± 0.49	1.89 ± 0.48[b]	1.80 ± 0.51[b]	1.76 ± 0.52
Male	2.04 ± 0.48[c]	2.07 ± 0.46[c]	1.94 ± 0.54[c]	1.91 ± 0.58[c]
Female	1.64 ± 0.42	1.68 ± 0.43	1.64 ± 0.43	1.60 ± 0.39

[a]Data are reported in N·m/kg as mean ± SD. AB, abduction; ACLR, anterior cruciate ligament reconstruction; AD, adduction.
[b]Significant difference between limbs ($P \leq .01$).
[c]Significant difference between men and women ($P \leq .05$).

(1.85 ± 0.49 N·m/kg) was significantly lower than that of the contralateral limb (1.89 ± 0.48 N·m/kg; t = 3.47; $P <$ .001; d = 0.29). Conversely, the hip AD torque of the ACLR limb (1.80 ± 0.51 N·m/kg) was significantly higher than that of the contralateral limb (1.76 ± 0.52 N·m/kg; t = 2.71; P = .004; d = 0.23).

Hip AB and AD strength LSI values are shown in Table 3. Visit 2 limb symmetry percentages were significantly greater compared with visit 1 values for both hip AB (t = 2.95; P = .02) and AD (t = 1.76; P = .04). There were no sex-based differences in muscle strength for AB (t = 0.20; P = .42; d = 0.03) or AD (t = 0.67; P = .25; d = 0.11).

Weak negative relationships were observed between the hip-to-thigh strength ratio group and PROs of the ACLR limb (Table 4). Correlations between AB/Q and all PROs for the ACLR limb were statistically significant (r = −0.2 to −0.24) except for the KOOS Activities of Daily Living (ADL) subscale. AB/H was significantly correlated only with KOOS ADL (r = −0.23) and ACL-RSI (r = −0.18). No significant correlations were observed between the agonist-to-antagonist strength ratio group and PROs of the ACLR limb, nor were any significant findings seen between any contralateral limb strength ratios and PROs.

A significant limb-by-time interaction ($F_{(1,85)} = 6.817$; $P = .01$) for hip AB strength was observed (Figure 5). At visit 1, the ACLR limb exhibited significantly weaker AB strength (ACLR: 1.80 ± 0.45 N·m/kg; contralateral: 1.86 ± 0.44 N·m/kg; $P < .001$; d = 0.51). At visit 2, the ACLR limb remained significantly weaker (ACLR: 1.88 ± 0.46 N·m/kg; contralateral: 1.91 ± 0.45 N·m/kg; P = .04; d = 0.19) but to a lesser magnitude. There was a significant increase in hip AB strength across visits for the ACLR limb (visit 1: 1.80 ± 0.45 N·m/kg; visit 2: 1.88 ± 0.46 N·m/kg; $t(85) = -2.64$; $P < .01$), but no significant change was found for the contralateral limb.

There was no significant limb-by-time interaction observed for hip AD; however, regardless of limb, hip AD strength was significantly greater at visit 2 (ACLR: 1.82 ± 0.48 N·m/kg; contralateral: 1.76 ± 0.47 N·m/kg) compared with visit 1 (ACLR: 1.70 ± 0.48 N·m/kg, $t(85) = -3.95$, $P < .01$; contralateral: 1.67 ± 0.47 N·m/kg, $t(85) = -3.31$, $P < .01$) (Figure 5). A significant increase in limb symmetry values was present for hip AB at visit 2 (98.70% ± 6.86%) compared with visit 1 (96.72% ±

TABLE 3
Hip Muscle Strength LSI Values According to Assessment Visit and Sex[a]

Variable	Hip Muscle Strength LSI, %	
	AB	AD
Visit 1 only (n = 140)	98.19 ± 6.04	102.79 ± 9.99
Visits 1 and 2 (n = 86)	Visit 1: 96.72 ± 5.83	Visit 1: 101.95 ± 8.16
	Visit 2: 98.70 ± 6.86[b]	Visit 2: 103.80 ± 12.05[c]
Men (n = 74)	98.29 ± 6.02	103.33 ± 11.94
Women (n = 66)	98.08 ± 6.11	102.20 ± 7.26

[a]Data are reported as a percentage (%) as mean ± SD. A limb symmetry index (LSI) of 100% indicates that the strength in the anterior cruciate ligament reconstruction (ACLR) limb and contralateral limb are equal; an LSI <100% indicates less strength in the ACLR limb, and an LSI >100% indicates more strength in the ACLR limb. AB, abduction; AD, adduction.
[b]Significant difference compared with visit 1 ($P \leq .01$).
[c]Significant difference compared with visit 1 ($P \leq .05$).

TABLE 4
Correlation Between Hip-to-Thigh Strength Ratios and PRO Scores at Visit 1[a]

Strength Ratio	Pearson *r*				
	IKDC	KOOS Symptoms	KOOS ADL	KOOS Sport/Rec	ACL-RSI
ACLR Limb					
Agonist to antagonist					
H/Q	−0.07	−0.09	0.15	−0.09	−0.05
AB/AD	0.06	−0.07	−0.02	0.05	−0.01
Hip to thigh					
AB/Q	−0.20[b]	−0.21[b]	−0.01	−0.20[b]	−0.24[c]
AB/H	−0.12	−0.10	−0.23[c]	−0.14	−0.18[b]
AD/Q	−0.23[c]	−0.17	−0.01	−0.22[b]	−0.25[c]
AD/H	−0.18[b]	−0.08	−0.25[c]	−0.19[b]	−0.21[b]
Contralateral Limb					
Agonist to antagonist					
H/Q	−0.02	−0.14	−0.05	−0.07	−0.05
AB/AD	0.13	−0.01	0.05	0.11	0.05
Hip to thigh					
AB/Q	0.11	−0.04	0.11	0.06	−0.028
AB/H	0.11	0.11	0.12	0.13	0.03
AD/Q	−0.04	−0.04	0.02	−0.07	−0.08
AD/H	−0.002	0.10	0.06	0.02	−0.02

[a]AB, abduction; ACL-RSI, Anterior Cruciate Ligament–Return to Sport after Injury score; ACLR, anterior cruciate ligament reconstruction; AD, adduction; ADL, Activities of Daily Living; H, hamstring; IKDC, International Knee Documentation Committee Subjective Knee Form; KOOS, Knee injury and Osteoarthritis Outcome Score; PRO, patient-reported outcome; Q, quadriceps; Sport/Rec, Sport and Recreation.
[b]Statistically significant ($P < .05$).
[c]Statistically significant ($P < .01$).

5.83%; $t = -2.95$; $P = .002$), approaching 100% LSI between the 2 limbs. A significant increase in limb symmetry values was also present for hip AD at visit 2 (103.80% ± 12.05%) compared with visit 1 (101.95% ± 8.16%; $t = -1.76$; $P = .041$), moving in a more asymmetric fashion away from 100% LSI between the 2 limbs.

DISCUSSION

The findings from the current study highlighted a pattern of hip AB weakness in the ACLR limb compared with the contralateral limb, which was accompanied by greater hip AD strength on the ACLR limb compared with the contralateral limb. The pattern of hip AB weakness and increased AD strength of the ipsilateral limb is seemingly not influenced by sex. Finally, we observed that hip AB and AD muscle strength and hip AB symmetry improved over the course of rehabilitation after ACLR.

The observation of hip AB weakness accompanied by an increased hip AD strength compensation of the ACLR limb compared with the contralateral limb was an unexpected finding because of the pattern traditionally observed of underloading the entire ACLR limb in patients recovering from surgery.[37] It is believed that underloading of the entire ACLR limb would lead to a more uniform pattern of muscle weakness within the same limb. However, in the current study, we observed that hip AD strength was greater in the ACLR limb compared with the contralateral limb, which may be evidence of a within-limb compensation among muscle groups acting on the same limb. One possible explanation for this unique observation could be an underloading of the hip AB musculature concurrently with an overloading compensation of the hip AD muscles on the reconstructed limb in patients with unilateral ACLR. Contemporary reports of underloading have theorized that the entire limb is affected.[37] The results of the current study challenge this notion, as we have observed a potential within-limb compensatory pattern in patients recovering from ACLR.

The unexpected within-limb strength differences may be explained through movement compensations as the observed pattern of muscle strength recovery in the current study has similarities to prior research. Previously, patients with ACLR have exhibited pelvic drop during a single-leg vertical drop jump after a fatiguing protocol, which was potentially attributed to hip AB weakness.[32,38,39] Further, pelvic drop has been associated with an increase external knee adductor moment during ambulation and single-leg vertical drop jumping,[32] which has been previously used as a medial tibiofemoral compartment loading indicator for individuals with knee joint degeneration such as knee osteoarthritis after ACLR.[14,32,47] Hip AB muscle weakness and greater strength of the hip AD muscles of the ACLR limb compared with the contralateral limb could further highlight compensations such as a pelvic drop, increased external knee AD moment, and increased compressive loads on the medial tibiofemoral compartment.[15] Previous research has described the consequences of decreased activation from the gluteus medius, which can be indicative of muscle weakness, in an ACLR population during dynamic functional activities.[6,9] The presence of gluteus medius weakness can elicit a valgus collapse at the knee, which is a vulnerable position and a signature risk factor for ACL injury and reinjury.[6,9,20,36,46] Additionally, reduced electromyographic activation of the hip AB muscles, including the gluteus medius and tensor fascia latae, has been accompanied with a simultaneous increase in activation of the adductor longus, a hip AD muscle, during a lateral pelvic drop stance.[40] This pattern of reduced AB activity and increased AD activity may highlight an area of focus for future research. It is important to note that neither pelvic drop nor surface electromyography during walking was measured in the current study and should be a focus of future research to determine whether hip muscle activation differences during movement can explain the strength changes observed in the current study.

The influence of sex has been well-documented for strength outcomes, where men tend to have greater hip abductor strength values than women.[25,43] Reduced hip strength, which we observed in women, has been shown in previous studies to be associated with risky dynamic valgus positioning during physical activities such as jumping and landing.[4,12,25,28,33] The lower hip strength found in the previously mentioned studies was attributed to some women's poor hip neuromuscular control, which potentially could be because of deficits in hip AB strength, specifically in the gluteus medius.[22,25,48] However, it has also been reported that there were no differences between male and female hip strength outputs.[24] The findings from the current study agree with previous research in which men were found to be stronger than their female counterparts[25,43]; however, the current study adds to the conflicting findings by suggesting that sex did not affect strength improvements in patients after ACLR 6 months after surgery. It is important to consider that sex differences may be innate and not a product of the surgical reconstruction or recovery progression. If strength differences between sexes contribute to knee injury risk, clinicians might consider alternative rehabilitation plans for men and women.

In the current study, negative weak-moderate relationships were observed between the hip-to-thigh strength ratio group of the ACLR limb and PROs; however, no relationships were observed between agonist-to-antagonist ratio groups and PROs. Specifically, H/Q or hip AB/AD muscle ratios have been commonly used to evaluate the strength balance of the antagonistic muscle to the agonistic muscle in order to highlight muscle strength imbalances and stability and to estimate risk of ACL injury and reinjury.[7,8,10,27,30,43,46] Conversely, the current study results suggest that when investigating the relationship between patient-reported function, a more holistic approach could be beneficial. During functional movement, from ambulation to sport performance, the body is utilizing the interconnected kinetic chain to produce movement.[26] The PROs used in this study evaluate how the individual is overall functioning with regard to one's ACLR knee. By only including the thigh (ie, H/Q ratio) or hip (ie, AB/AD) agonist-to-antagonist strength ratio, important pieces of the kinetic chain are not being represented and therefore potentially make an incomplete model of the lower extremity strength balance between antagonist and agonist musculature.

Weak negative relationships were observed between the hip-to-thigh strength ratio group and PROs, indicating that as the strength ratio value decreased, the functional outcome recorded through the PROs improved. A hip-to-thigh strength ratio ≥ 1 would indicate that the hip muscle (eg, hip AB and AD muscles) in question is stronger than or equally balances out the thigh muscle (eg, quadriceps and hamstring muscles) in question. Conversely, a ratio < 1 indicates that the thigh muscle produces larger strength values compared with the hip muscle. For example, in the current study we observed that as the AB/Q strength ratio decreased, indicating that an individual increased the amount of quadriceps strength compared with hip abductor strength, one's subjective knee function improved. Strength ratios >1 may potentially indicate that the individual is utilizing a hip muscle strategy, stemming from the greater hip strength values, to a greater extent than a thigh muscle strategy during movement, while hip-to-thigh strength ratios <1 may indicate that the individual is utilizing a thigh muscle strategy to a greater extent than the hip. Further

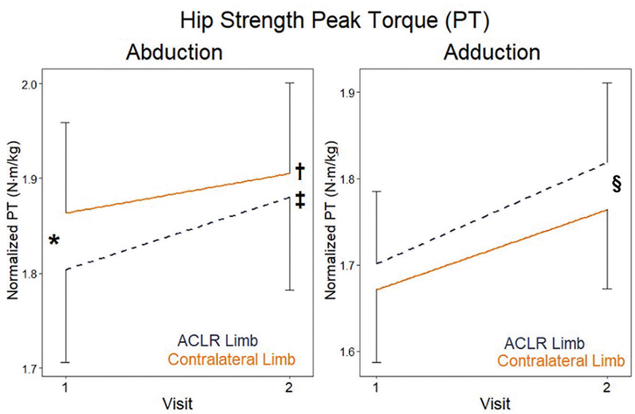

Figure 5. Mean hip abduction and adduction strength changes across visits 1 and 2. *Significant difference at visit 1 between the anterior cruciate ligament reconstruction (ACLR) and contralateral limbs ($P < .001$). †Significant difference at visit 2 between ACLR and contralateral limbs ($P = .04$). ‡Significant difference in the ACLR limb between visits 1 and 2 ($P < .01$). §Significant difference in both the ACLR and contralateral limbs between visits 1 and 2 ($P < .01$).

investigation into this ratio and movement kinematics during functional tasks is warranted. A negative relationship is expected: as the thigh musculature begins to regain strength—which is commonly lost after reconstruction—back to the preinjury level, a patient's perceived function should increase along with his or her confidence to participant in RTP activities.[3] This study suggests that hip-to-thigh strength ratios might be a more appropriate indicator of subjective function recovery than the traditionally used agonist-to-antagonist strength ratio.

Over the 2 testing sessions we observed an increase in hip strength bilaterally for both AB and AD muscles; however, hip AB strength increased at a quicker rate in the ACLR limb than the contralateral limb (Figure 5). Despite these strength improvements, the ACLR limb still exhibited strength deficits in hip AB musculature and greater strength in the hip AD musculature compared with the contralateral limb at both visits. The hip AB strength deficit of the ACLR limb compared with the contralateral limb that was present at the first visit was still observed at the second visit; however, over time the AB hip strength symmetry percentage improved on average 1.98%, therefore becoming more symmetrical (see Table 3). It is currently unclear as to whether this improvement is a clinically important increase in hip strength symmetry. The significant results from this study presented with varying effect sizes ranging from moderate to weak. Similar effect sizes for hip strength for between- and within-group comparisons have also been observed in previous studies.[12,19,24] Although the magnitude of changes observed was small, these changes may have long-lasting effects when repeated over a lifetime of physical activity. However, based on the results of the current study, we cannot draw conclusions on the lasting impact of hip strength deficits after ACLR. This is an area that needs further research and consideration.

Our findings suggest a significant moderate magnitude of hip AB strength deficit in the ACLR limb compared with the contralateral limb ($d = 0.51$) at visit 1 approximately 4.8 months after surgery. This magnitude decreases ($d = 0.19$) at visit 2 approximately 8.2 months after surgery, when the strength deficit is much lower between the ACLR and contralateral limbs. This reduction in magnitude of difference between limbs across visits was expected, as patients are further along in their recovery by visit 2, and the finding suggests that patients are continuing to recover hip strength at later stages of rehabilitation. Conversely, the hip AD strength symmetries appeared to increase further away from 100% symmetry and therefore worsen over time. It is unclear as to whether hip AB strength continues to improve or if hip AD strength of the ACLR and contralateral limb start to become more symmetrical over time past the 8-month mark after surgery.

The persistence or an increase of these small strength deficits over time between limbs could lead to increased pain, deterioration of the knee cartilage, joint space narrowing, compressive loads on the medial tibiofemoral compartment, and a potentially increased risk for early-onset osteoarthritis and a further decrease in the patient's quality of life.[14,32,38,41] These findings highlight the utility of incorporating serial objective assessments in patients' standard of care to accurately target specific musculature throughout rehabilitation so that deficiencies and asymmetries do not go unnoticed and therefore untreated, potentially putting individuals at greater risk for reinjury.[9]

Limitations

The present findings suggest that there is a low magnitude of change in hip strength over time, with LSI values oscillating closely around 100% symmetry between limbs (see Table 3). The complex characteristics of the hip joint and the surrounding musculature can make it difficult for researchers to measure precisely. There is no gold standard technique for how to measure hip strength, which makes it difficult to compare across other research studies.[12] Our study measured hip strength using the ForceFrame (Vald Performance) device, which has been found to have good reliability,[10] in a force unit of measurement and then converted it to torque, whereas knee strength was collected with a different device in torque unit of measurement, which could have influenced our results. Additionally, the isometric bilateral measurement technique might not be the optimal method for evaluating isolated hip AB or AD strength because of the potential contributions from hip external and internal rotational torque. Moreover, this hip strength measurement technique might not be ideal in ACLR populations because of the potential for underestimating the limb differences and the dynamic nature of the injury in general. However, the isometric nonweightbearing technique used in this study, with patients in a supine hook-lying position, allows for individuals to safely engage in the strength test procedure earlier in the rehabilitation phase. It is also possible that utilizing a unilateral testing approach or testing under rested versus fatigued conditions could provide additional insight into the role of hip muscle function on ACLR outcomes.

Another limitation in the current study is that regardless of each patient receiving a standard-of-care rehabilitation protocol from an orthopaedic surgeon after ACLR, the rehabilitation protocol that each patient completed during the recovery process was not recorded or standardized. The compliance of each patient to complete the rehabilitation protocol could have influenced the results of this study. Additionally, patients attended testing sessions ad hoc after surgery, which limited the uniformity of our patients' time after surgery.

We observed that patients increased their hip strength over time; however, there were still deficits between limbs for patients who attended 2 visits. We were not able to assess whether these strength deficits persist for >8 months after ACLR. Long-term follow-up assessments should be conducted to examine hip strength recovery as well as patient status (eg, reinjury status, whether the patient successfully returned to sport or physical activity, etc) to highlight the clinical importance of hip strength after ACLR.

CONCLUSION

At the time of RTP assessment, the ACLR limb had weaker hip AB and stronger AD compared with the contralateral limb. Hip muscle strength recovery was not influenced by sex. Hip strength and symmetry improved over the course of rehabilitation. Although strength differences across limbs were minor, the clinical importance of these differences is still unknown.

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