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Hip external rotation strength predicts hop performance after anterior cruciate ligament reconstruction

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Abstract
Purpose Quadriceps strength and single-leg hop performance are commonly evaluated prior to return to sport after anterior cruciate ligament reconstruction (ACLR). However, few studies have documented potential hip strength deficits after ACLR, or ascertained the relative contribution of quadriceps and hip strength to hop performance.
Methods Patients cleared for return to sports drills after ACLR were compared to a control group. Participants' peak isometric knee extension, hip abduction, hip extension, and hip external rotation (HER) strength were measured. Participants also performed single-leg hops, timed hops, triple hops, and crossover hops. Between-limb comparisons for the ACLR to control limb and the non-operative limb were made using independent two-sample and paired sample *t* tests. Pearson's correlations and stepwise multiple linear regression were used to determine the relationships and predictive ability of limb strength, graft type, sex, and limb dominance to hop performance.
Results Sixty-five subjects, 20 ACLR [11F, age 22.8 (15–45) years, 8.3 ± 2 months post-op, mass 70.47 ± 12.95 kg, height 1.71 ± 0.08 m, Tegner 5.5 (3–9)] and 45 controls [22F, age 25.8 (15–45) years, mass 74.0 ± 15.2 kg, height 1.74 ± 0.1 m, Tegner 6 (3–7)], were tested. Knee extension (4.4 ± 1.5 vs 5.4 ± 1.8 N/kg, $p = 0.02$), HER (1.4 ± 0.4 vs 1.7 ± 0.5 N/kg, $p = 0.04$), single-leg hop (146 ± 37 vs 182 ± 38% limb length, $p < 0.01$), triple hop (417 ± 106 vs 519 ± 102% limb length, $p < 0.01$), timed hop (3.3 ± 2.0 vs 2.3 ± 0.6 s, $p < 0.01$), and crossover hop (364 ± 107 vs 446 ± 123% limb length, $p = 0.01$) were significantly impaired in the operative versus control subject limbs. Similar deficits existed between the operative and non-operative limbs. Knee extension and HER strength were significantly correlated with each of the hop tests, but only HER significantly predicted hop performance.
Conclusions After ACLR, patients have persistent HER strength, knee extension strength, and hop test deficits in the operative limb compared to the control and non-operative limbs, even after starting sport-specific drills. Importantly, HER strength independently predicted hop performance. Based on these findings, to resolve between-limb deficits in strength and hop performance clinicians should include HER strengthening exercises in post-operative rehabilitation.
Level of evidence Prognostic Study, Level II.

Keywords ACL · Hip strength · Rehabilitation · Quadriceps

Abbreviations
ACLR Anterior cruciate ligament reconstruction
HER Hip external rotation
RTS Return to sport

Introduction

Between 130,000 and 175,000 anterior cruciate ligament reconstructions (ACLRs) are performed annually in

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the USA with only 44–55% of all patients returning to competitive sport [1, 2, 23]. Of those who return to sport (RTS), 11.1–29.5% experience a second ACL injury in the same or contralateral knee [42]. Poor RTS outcomes have generated significant discussion regarding the criteria used to assess athlete readiness for RTS after ACLR [1, 22, 24].

Of the objective RTS criteria described, quadriceps strength and single-leg hop tests are the most commonly assessed [22]. Quadriceps muscle weakness following ACLR has been well documented and is a significant risk factor for re-injury after RTS [9, 18, 33]. Furthermore, athletes achieving ≥90% symmetry in quadriceps strength and single-leg hop testing compared to the non-injured limb were reinjured less frequently [9]. Despite the recommended utilization of quadriceps strength and hop testing in RTS decision-making, there appears to be a minimal relationship between the two measures [10, 37]. A lack of relationship between quadriceps strength and hop testing suggests that the two measures assess different constructs in recovery from ACLR and highlights the need to explore the contribution of weakness in other muscle groups, such as the hip, to hop performance.

While less commonly studied than quadriceps strength, hip muscle weakness has also been described after ACLR [5, 14, 33]. Interestingly, several prospective studies have linked hip dysfunction to knee biomechanics associated with increased incidence of lower extremity injury [7, 12, 13, 39]. Despite these findings, hip muscle strength is not often used as a RTS criterion or evaluated in terms of ACL re-injury risk. Likewise, the relationships between hip strength and common RTS criteria such as single-leg hop testing have yet to be elucidated. Given the contribution of the hip musculature in both propulsion and eccentric control during single-leg landings, deficits in hip strength may play a role in impaired hop performance after ACLR [4, 13].

The purpose of this study was to compare the isometric hip and quadriceps muscle strength and single-leg hop test performance of the ACLR extremity to a control group, as well as to the non-operative extremity. This study also sought to examine the relationship between hip and quadriceps muscle strength with performance on single-leg hop tests. It was hypothesized that ACLR patients would have persistent muscle strength and hop test deficits and that hip muscle strength would be more closely related to hop test performance than quadriceps strength. Additionally, it was hypothesized that hip muscle strength would better predict hop test performance than quadriceps strength, sex, graft type, and limb dominance.

Materials and methods

ACL reconstruction patients and controls

Patients included in the ACLR group were recruited from eligible patients at the University's outpatient sports medicine clinic. Inclusion criteria included: (1) at least six months status post-ACL reconstruction with hamstring or bone-patellar tendon-bone (BPTB) autograft, (2) no injury to the ipsilateral or contralateral limb in the prior 3 months, (3) no previous history of injury or surgery to the contralateral limb that may affect hip or knee function, and (4) cleared for return to sport drills and sport-specific training by their physical therapist and surgeon. Patients were excluded if they had any of the following: (1) a history of other ligamentous injuries to either knee, (2) knee effusion in either knee, (3) positive Lachman's test in either knee, or (4) positive pivot shift in either knee.

Participants included in the control group were recruited from a sample of convenience. Flyers and recruitment emails were distributed amongst university classes and throughout the community. To be included, all participants were in good general health and met the following inclusion criteria: (1) age between 18 and 45 years, (2) currently free of any trunk, hip, or knee injuries within the last three months, and (3) no previous history of injury or surgery that may affect their trunk, hip, or knee function. At the time of data collection, all participants completed a Tegner activity scale to quantify their current physical activity level and declared their pre-injury limb dominance.

Strength testing

Participants completed a series of isometric lower extremity strength tests: hip abduction, hip extension, hip external rotation, and knee extension. Tests were performed by two male assessors using a hand-held dynamometer (Lafayette Instruments, Lafayette, IN) secured by a stabilization strap, as previously described and validated [3, 41]. One practice and three experimental trials were performed for 5, with 15 s of rest between contractions. The average of the three experimental trials was used for calculations. To allow for comparison between groups, the experimental trials were normalized to body mass by dividing the strength value by the subject's weight in kilograms. Hip abduction strength was tested with the subject lying in the sidelying position. Hip extension strength was tested with participants in the prone position and the knee flexed to 90°. Hip external rotation strength was tested with participants in the seated position, with the knee and hip flexed to 90°. Knee extension strength was tested with the participant in the sitting position, the examined thigh parallel to the floor, and the leg hanging off the table in a vertical position with the knee flexed to 90°.

Single-leg hop testing

Participants in each group performed a series of single-leg hop tests as described and validated [17, 21, 25, 35, 36]. This battery of hop tests included a single-leg hop for distance, a timed 6-m hop, a triple hop for distance, and a crossover hop for distance. For all of the tests, the participant was required to start from a resting single-leg stance. ACLR participants performed with their non-operative limbs first to prevent inadvertently biasing the performance of the non-operative limb to match the performance of the operative limb. One trial hop followed by two measured hops was performed for each test [35]. The average value of the measured hops was used for later calculations. To allow for comparison between groups, hop distances were normalized to limb length by dividing the distance by limb length as measured from the anterior superior iliac spine to the medial malleolus [25]. The Institutional Review Board of the University of Kentucky approved this study (13-0326-P1H).

Statistical analysis

Comparisons between the operative and non-operative limb for the ACLR group were made using two-tailed paired samples *t* tests to compare knee strength, hip strength, and single-leg hop performance. To compare the ACLR operative limb with the control group and for comparisons of sex, limb dominance, and graft type in the ACLR group, independent two-sample *t* tests were utilized. As an ordinal variable, the Tegner activity scale was compared using a Mann–Whitney *U* test. Muscle strength and hop performance variables identified as significantly different between groups or between limbs were included in subsequent correlational analyses. Pearson's product moment correlation coefficients were calculated to assess the relationship between limb strength and hop performance. Subsequently, only those relationships which were significantly correlated were entered into a stepwise multiple linear regression along with sex, limb dominance, and graft type to determine the predictability of hip and knee strength measures on single-leg hop performance in the ACLR operative limb. PASW Statistics version 18.0 (SPSS Inc, Chicago, IL, USA) was utilized for all limb comparisons, correlations, and linear regression analyses. Statistical significance was defined as $p \leq 0.05$. To detect an effect size of 0.5 at $\alpha = 0.05$ and $\beta = 0.8$, a sample size calculation revealed a need for a minimum of 17 subjects per group.

Results

A total of 65 participants (20 ACLR, 45 controls) completed the study. No significant differences in mean age, height, weight, or Tegner activity level between the ACLR and control groups were present at the time of testing (Table 1).

There was a significant difference between the ACLR operative limb and control limb in hip external rotation strength, knee extension strength, single-leg hop, timed hop, triple hop, and crossover hop, with the ACLR operative limb significantly weaker and demonstrating poorer performance in each hop test (Table 2). There were no significant differences in hip abduction strength or hip extension strength. Similar results were observed when comparing the ACLR operative to the non-operative limb (Table 3).

Males significantly outperformed females in all four hop tests in the ACLR limb. There were no significant differences when the ACLR group was stratified by injury to the dominant or non-dominant limb. Lastly, subjects with BPTB autograft demonstrated greater hip extension strength, hip external rotation strength, hip abduction strength, and single-leg hop performance compared to subjects with hamstring autograft. For complete results by sex, limb dominance, and graft type, refer Table 4.

Significant correlations were found between hip external rotation and knee extension strength, and

Table 1 Subject demographics

	Number	Age (years)	Sex	Weight (kg)	Injured side	Follow-up (months)	Graft type	Tegner
ACLR	20	22.8 (15–45)	11 female, 9 male	70.5 ± 12.9	8 left, 12 right	8.3 (6–14)	8 Hamstring autograft, 12 BPTB autograft	5.5 (3–9)
Controls	45	25.8 (15–45)	22 female, 23 male	74.0 ± 15.2	–	–	–	6 (3–7)
p value	–	0.097	0.649	0.370	–	–	–	0.761

Data presented as mean ± standard deviation or mean (range)

Tegner presented as median (range)

– not applicable, *ACLR* anterior cruciate ligament reconstruction, *BPTB* bone-patellar tendon-bone

Table 2 Comparison of muscle strength and hop test performance between ACLR and control group limbs

Test	ACLR	Controls			
	Mean	Mean	% Difference	95% CI	*p* value
Hip extension	2.9 ± 1.1	3.1 ± 1.0	−6.7	−0.8, 0.4	n.s.
Hip external rotation	1.4 ± 0.4	1.7 ± 0.5	**−19.4**	−0.5, −0.1	0.04*
Hip abduction	4.1 ± 0.7	4.3 ± 1.0	−4.8	−0.6, 0.4	n.s.
Knee extension	4.4 ± 1.5	5.4 ± 1.8	**−20.4**	−1.9, −0.2	0.02*
Single-leg hop	146 ± 37	182 ± 38	**−22**	−56, −16	<0.01*
Timed hop (s)	3.3 ± 2.0	2.3 ± 0.6	**35.7**	0.4, 1.6	<0.01*
Triple hop	417 ± 106	519 ± 102	**−21.8**	−156, −46	<0.01*
Crossover hop	364 ± 107	446 ± 123	**−20.2**	−147, −18	0.01*

Statistically significant differences in bold; hop test results normalized for limb length

Strength tests reported in N/kg. Hop tests reported as % of limb length, unless otherwise specified

95% CI 95% confidence interval for mean difference between ACLR and controls

ACLR Anterior cruciate ligament reconstruction

± Standard deviation

* Statistically significant

Table 3 Between-limb comparison of muscle strength and hop test performance in ACLR group

Test	ACLR extremity	Non-operative extremity			
	Mean	Mean	% Difference	95% CI	*p* value
Hip extension	195.4 ± 70.7	193.6 ± 44.6	0.9	−21.7, 25.3	n.s.
Hip external rotation	101.6 ± 33.7	114.4 ± 36.7	**−11.9**	−25.6, −0.1	0.05*
Hip abduction	287.8 ± 56.5	287.1 ± 59.1	0.2	−22.9, 24.4	n.s.
Knee extension	308.0 ± 120.1	366.4 ± 119.4	**−17.3**	−103.2, −13.6	0.01*
Single-leg hop	132 ± 37	162 ± 34	**−20.4**	−37, −22	<0.01*
Timed hop (s)	3.3 ± 2.0	2.5 ± 0.9	**27.6**	0.2, 1.5	0.02*
Triple hop	379 ± 105	452 ± 108	**−17.6**	−95, −51	<0.01*
Crossover hop	331 ± 107	390 ± 108	**−16.4**	−79, −38	<0.01*

Statistically significant differences in bold

Strength tests reported in Newtons; hop tests reported in cm, unless otherwise specified

95% CI 95% confidence interval for mean difference between ACLR and non-operative extremity

ACLR Anterior cruciate ligament reconstruction

±Standard deviation

* Statistically significant

performance on all hop tests (Table 5). Stepwise multiple linear regression models revealed hip external rotation as the sole predictor of hop performance (single-leg hop $b = 0.833$, $p = 0.000$; triple hop $b = 2.23$, $p = 0.000$; timed hop $b = -0.034$, $p = 0.007$; crossover hop $b = 2.37$, $p = 0.000$). The R^2 of the models was 0.56, 0.48, 0.30, and 0.56, respectively.

Discussion

The most important finding of the present study was the presence of isometric hip external rotation weakness which predicted single-leg hop performance independent of knee extension strength after ACLR. Despite recommendations that hip strength be assessed after ACLR, little is known about hip muscle weakness following ACL reconstruction [6, 11]. The results of the current study partially agree with previous investigations of hip strength impairments after ACLR, which also found no differences in hip abduction strength in a cohort of females 7 months post-ACLR [28]. However, in contrast, the current study found that ACLR subjects had significantly weaker hip external rotation strength than controls while the previous study reported no significant differences [28]. Differences in hip external rotation strength between this and the former study may be partially due to the mixed gender cohort and lower Tegner score at the

Table 4 Comparison of muscle strength and hop test performance of the ACLR extremity in the ACLR group stratified by sex, limb dominance, and graft type

Test	Male	Female	*p* value	Dominant limb injured	Non-dominant limb injured	*p* value	BPTB autograft	Hamstring autograft	*p* value
Hip extension	2.7 ± 1.2	3.0 ± 1.0	n.s.	3.0 ± 1.0	2.7 ± 1.2	n.s.	3.3 ± 1.1	2.3 ± 0.7	0.03*
Hip external rotation	1.6 ± 0.5	1.4 ± 0.4	n.s.	1.5 ± 0.4	1.4 ± 0.5	n.s.	1.7 ± 0.4	1.1 ± 0.3	0.01*
Hip abduction	4.3 ± 0.8	4.0 ± 0.5	n.s.	4.3 ± 0.7	3.9 ± 0.6	n.s.	4.4 ± 0.7	3.8 ± 0.4	0.04*
Knee extension	4.5 ± 1.6	4.3 ± 1.4	n.s.	4.3 ± 1.6	4.4 ± 1.4	n.s.	4.8 ± 1.7	3.8 ± 0.8	n.s.
Single-leg hop	164 ± 36	130 ± 32	0.04*	148 ± 41	142 ± 34	n.s.	159 ± 36	126 ± 30	0.04*
Timed hop	2.3 ± 0.7	4.2 ± 2.3	0.03*	3.5 ± 2.3	3.1 ± 1.6	n.s.	2.6 ± 1.2	4.4 ± 2.5	n.s.
Triple hop	479 ± 95	367 ± 89	0.02*	427 ± 126	406 ± 81	n.s.	453 ± 109	363 ± 79	n.s.
Crossover hop	429 ± 91	305 ± 87	0.01*	361 ± 123	367 ± 89	n.s.	399 ± 103	303 ± 91	n.s.

Strength tests reported in N/kg. Hop tests reported as % of limb length, except the timed hop which is reported in seconds

ACLR Anterior cruciate ligament reconstruction, *BPTB* bone-patellar tendon-bone

Data presented as mean ± standard deviation

* Statistically significant

Table 5 Pearson correlations between limb strength and hop performance of the ACLR limb

	Single-leg hop	Triple hop	Timed hop	Crossover hop
Hip external rotation	0.765 (.000)*	0.714 (.000)*	−0.579 (.007)*	0.766 (.000)*
Knee extension	0.554 (.011)*	0.513 (.021)*	−0.426 (n.s.)	0.461 (.047)*

Data presented as *r* value (*p* value)

* Statistically significant at $p < 0.05$

time of testing in the current cohort compared to the previous study (5.5 vs 6.5). Additionally, one previous study also reported no difference in isometric hip external rotation strength in the ACLR limb compared to a control group, but the participants in this study were greater than 3 years post-ACLR, as compared to 8 months post-ACLR in the current study [5]. As such, a direct comparison between the two studies is difficult, and differences are likely due to the variability in time points used for testing. Nonetheless, these data suggest that hip external rotation strength deficits are present at time of return to sport after ACLR and represent a potential area for additional intervention during post-operative rehabilitation.

The current study's finding of reduced hip external rotation strength in the ACLR group is notable in light of a several prospective studies linking hip muscle function to ACL injury risk. For instance, Paterno et al. [32] identified reduced contralateral hip external rotation torque production as a significant predictor of a second ACL tear. Additionally, Khayambashi et al. [15] demonstrated that hip external rotation strength independently predicted non-contact primary ACL injury in a large prospective study of male and female competitive athletes. The findings of this study extend those of previous studies by providing evidence that hip external rotation strength remains impaired following rehabilitation, possibly contributing to impaired performance and heightened injury risk. These results suggest the need for hip external rotation strengthening exercises during rehabilitation after ACLR. To date, only one study has evaluated the efficacy of an isolated hip strengthening intervention during post-ACLR rehabilitation [8]. This study demonstrated minimal differences in 3-month knee extension range of motion, pain rating, and International Knee Documentation Committee scores compared to the group that did not receive early hip strengthening during rehabilitation. However, this study did not assess hip strength at any time during the study to determine whether baseline impairments in hip strength were present and/or were improved after the intervention [8]. The lack of objective hip strength assessment makes it difficult to assess whether any improvements in hip strength were achieved, possibly accounting for lack of significant findings. Based on data presented in the current study, additional investigations into the role of hip external rotation strengthening exercises during recovery from ACLR on subsequent sport performance and injury are needed.

The findings of significantly reduced knee extension strength and single-leg hop performance compared to controls are consistent with previous studies of knee extension strength deficits and hop performance at several time points after ACLR [19, 30, 31, 33, 34]. Recovery of quadriceps strength has been cited as an important factor in achieving a successful outcome after ACLR [16, 34, 38]. Assessments of quadriceps strength and hop performance are commonly performed to provide objective criteria for return to sport [24, 35]. However, the relationship between quadriceps strength and single-leg hop performance is variable, suggesting that other factors contribute to improved hop performance [11]. In the current study, while both knee extension strength and hip external rotation strength were significantly related to hop performance, the relationship with hip external rotation strength was the strongest (Table 5). A recent review of the measurement properties of single-leg hop tests noted limited and conflicting evidence regarding the tests' abilities to predict injury [10]. It should be noted, however, that the value of single-leg hop assessments in RTS testing may be from these tests serving as valuable benchmarks for recovery from ACLR. Of the single-leg hop tests utilized in the current study, the single-hop for distance is the most studied and demonstrates good discriminative validity in males after ACLR [10, 26]. Additionally, the single-leg hop for distance is responsive to improvements in performance after ACLR [10, 40]. Thus, improvement in single-hop performance during rehabilitation from ACLR may further determine the degree of recovery achieved. Without additional evidence on how hop test performance contributes to future injury risk or readiness for RTS after ACLR, it is difficult to derive absolute meaning from observed asymmetries for an individual athlete. However, the minimal equipment demands associated with hop testing, the discriminative validity of the single-hop test after ACLR, responsiveness to rehabilitation, and the inclusion of hop testing for limb symmetry in successful RTS testing batteries suggest there is clinical utility in administering single-leg hop testing in patients after ACLR [9, 10, 18].

The results of this study highlight the need to address hip external rotation strength deficits during rehabilitation after ACLR. It was found that when knee extension strength, hip external rotation strength, sex, graft type, and injury to dominant or non-dominant limb were entered into a regression model, only hip external rotation strength was a significant predictor of hop performance and independently predicted between 30 and 56% of the variance in performance. Hopping for maximum distance demands large amounts of muscle power to propel the body forward and to control the landing. As one of the most powerful muscles in the human body, and a significant contributor to trunk control during dynamic lower extremity tasks [20, 29], the gluteus maximus is critical for performance of the hopping tasks. This may explain why patients who have sufficient post-operative quadriceps strength recovery continue to demonstrate asymmetries in hop testing performance, and points to possible global muscle strength impairment in the ACLR limb. Active hip external rotation, as tested in this study, consists mostly of gluteus maximus recruitment [20, 27]. Other muscles commonly associated with hip external rotation, such as the piriformis and short external rotators, have little or no effect on external rotation when the hip is flexed to 90° [27]. Interestingly, despite differences observed in hip external rotation strength, hip extension strength was not significantly different between the ACLR, non-operative limb, or control group. Testing was performed in prone with the knee flexed to 90° and the lumbar spine stabilized with a strap to limit the contribution of the hamstrings and lumbar extensors, respectively. However, contributions from these muscle groups may have masked gluteal weakness during hip extension. Future work should investigate the efficacy of hip strengthening intervention on reducing biomechanical risk factors for second ACL injury, rate of successful return to sport, and the role of improved hip strength on psychological factors related to recovery after ACLR. These studies will further clarify the significance of proximal weakness and identify the most successful means of intervention to improve hip strength in this population.

There are several limitations of the current study. First, the study was cross-sectional and thus potential associations between muscle weakness or hop performance with future injury risk cannot be made. Additionally, hip strength was not assessed pre-operatively or at prior time points post-operatively so baseline differences cannot be accounted for nor can the time of onset of hip external rotation weakness be established. Lastly, although isometric strength testing is the assessment method most easily reproduced in a clinical setting, it does not reflect how these muscles perform during dynamic activities like hopping.

The findings of this study showed that isometric hip external rotation weakness is present after ACLR and is predictive of single-leg hop performance. Based on these findings, interventions to increase hip external rotation strength should be included as part of rehabilitation after ACLR in order to achieve better and potentially more symmetrical single-leg hop performance.

Conclusions

Patients after ACLR have significant deficits in hip external rotation strength, knee extension strength, and single-leg hop performance with hip external rotation strength independently predicting single-leg hop performance. Although quadriceps strengthening should continue to be an important component of rehabilitation after ACLR, patients may also benefit from exercises to improve hip external rotation strength to facilitate better dynamic limb function.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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