Strength Asymmetry and Landing Mechanics at Return to Sport after Anterior Cruciate Ligament Reconstruction

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ABSTRACT

SCHMITT, L. C., M. V. PATERNO, K. R. FORD, G. D. MYER, and T. E. HEWETT. Strength Asymmetry and Landing Mechanics at Return to Sport after Anterior Cruciate Ligament Reconstruction. *Med. Sci. Sports Exerc.*, Vol. 47, No. 7, pp. 1426–1434, 2015. **Purpose**: Evidence-based quadriceps femoris muscle (QF) strength guidelines for return to sport after anterior cruciate ligament (ACL) reconstruction are lacking. This study investigated the effect of QF strength asymmetry on knee landing biomechanics at the time of return to sport after ACL reconstruction. **Methods**: Seventy-seven individuals (17.4 yr) at the time of return to sport after primary ACL reconstruction (ACLR group) and 47 uninjured control individuals (17.0 yr; CTRL group) participated. QF strength was assessed and quadriceps index was calculated (QI = [involved strength / uninvolved strength] × 100%). The ACLR group was subdivided based on QI: high quadriceps (HQ, QI ≥ 90%) and low quadriceps (LQ, QI < 85%). Knee kinematic and kinetic variables were collected during a drop vertical jump maneuver. Limb symmetry during landing and discrete variables were compared among the groups using multivariate analysis of variance and linear regression analyses. **Results**: The LQ group demonstrated worse asymmetry in all kinetic and ground reaction force variables compared to the HQ and CTRL groups, including reduced involved limb peak knee external flexion moments ($P < 0.001$), reduced involved limb ($P = 0.003$) and increased uninvolved limb ($P = 0.005$) peak vertical ground reaction forces and higher uninvolved limb peak loading rates ($P < 0.004$). There were no differences in the landing patterns between the HQ and CTRL groups on any variable ($P > 0.05$). In the ACLR group, QF strength estimated limb symmetry during landing after controlling for graft type, meniscus injury, knee pain, and symptoms. **Conclusions**: At the time of return to sport, individuals after ACL reconstruction with weaker QF demonstrate altered landing patterns. Conversely, those with nearly symmetrical QF strength demonstrate landing patterns similar to uninjured individuals. Consideration of an objective QF strength measure may aid clinical decision making to optimize sports participation after ACL reconstruction. **Key Words:** ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION, QUADRICEPS, WEAKNESS, LANDING, KINEMATICS, KINETICS

Anterior cruciate ligament (ACL) injury is a common knee injury with significant risk of future physical disability from increased risk of second ACL injury (26,27,32) and long-term joint morbidity such as early cartilage degeneration (17,21). Although an ACL reconstruction procedure is the standard of care for individuals who want to return to high-level activities, recent studies indicate that these individuals may be at high risk for poor outcome (13,26). Return-to-sport rates are relatively low after ACL reconstruction, with 63% resuming preinjury level of activity participation and only 44% returning to competitive sport (1). For those who do return to higher-level activities, second injury rates are as high as 24% in young, active individuals (26), with the highest risk of reinjury within the first 7 months after return to sport (13). The risk of poor outcome may be related to persistent deficits in muscle strength (29), deficits in athletic performance (18), and altered

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limb loading strategies during squatting (19), jumping, and landing activities (6,8,20,22,23,25) that are consistently noted after return to high-level activity in this population.

In light of suboptimal outcomes, return-to-sport decision making has been a recent focus, with an emphasis on the use of objective measures of impairment and functional status to guide this decision. Although most authors advocate limb symmetry in muscle strength and functional performance as indicators of readiness to resume activity (10,12), empirical data regarding appropriate criterion values for limb symmetry are sparse. Recent work shows that greater quadriceps femoris muscle (QF) strength asymmetries (>15% deficit, compared to the uninjured limb) at the time of return to sport are associated with worse performance on measures of function and performance in young, active individuals after primary ACL reconstruction (34). In the same cohort, athletes with minimal QF strength deficits (<10% deficit, compared to the uninjured limb) demonstrated functional performance that is similar to uninjured individuals (34). Although not a definitive indicator of a criterion value for QF strength for return to sport, this study (34) indicates that isometric QF strength deficits of >15% negatively affect clinical measures of function and performance at a time point when the individual is returning to high-level activities. However, less is known about the effect of QF strength asymmetries on the quality of movement patterns at this same time point.

Abnormal movement patterns are noted to persist as long as 2 yr after ACL reconstruction (2,6,8,22,23,25) and are implicated in the risk of second ACL injury (26) as well as the risk of knee osteoarthritis (4,14,15). Poor QF strength is implicated in abnormal movement patterns and asymmetrical limb loading strategies after ACL reconstruction (2,15,20). QF strength accounts for a significant portion of the variance in the sagittal plane knee angle and in moments during walking (15), jogging (2), and single-leg hopping (20). During walking and jogging, individuals with QF strength deficits (>20% deficit, compared to uninjured side) after ACL reconstruction show reduced sagittal plane knee joint angles and moments compared to those with symmetrical strength (<10% deficit, compared to uninjured side), whereas those with symmetrical QF strength demonstrated movement patterns that are indistinguishable from uninjured individuals (15). Individuals in this study (15) were tested at a minimum of 12 wk after surgery, with some individuals regularly participating in some activity (jogging, running, and swimming) and others participating in higher-level cutting and pivoting sports activities. Recently, a strong correlation (r^2 = 0.78) between QF strength and external knee flexion moments during a single-leg hop test was observed at 12 months after ACLR (20). In this analysis, all study participants had returned to active sports participation 7–8 months before testing (20). Studies show persistent deficits in QF strength and altered movement patterns for long after individuals with ACLR return-to-sport activities (2,15,20); however, to our knowledge, no studies have evaluated the effect of QF strength asymmetries during high-level dynamic activities at the critical time point of return to sport. Further, no studies have evaluated the relationship between QF strength and mechanics while accounting for the potential influence of other variables. This information will provide further insight into return-to-sport decision making.

The development of standardized, objective, and evidence-based recommendations for clinical decision making is crucial for the promotion of standards of care, the optimization of activity performance, and the potential to minimize risk of future injury in this population. In an effort to progress toward evidence-based guidelines for return-to-activity decision making, understanding the influence of key impairments, such as QF strength deficits, on movement patterns at the time of return to sport is imperative.

The purpose of this study was to investigate the effect of QF strength asymmetry at the time of return to sport on movement patterns during a high-level bilateral landing maneuver in young athletes after ACL reconstruction (ACLR group). For this analysis, the ACLR group was subdivided into a high quadriceps (HQ) group (those with a QF strength deficit of ≤10% in the involved limb compared to the uninvolved limb) and a low quadriceps (LQ) group (those with a QF strength deficit of >15% deficit in the involved limb compared to the uninvolved limb). The first hypothesis tested was that the LQ group would demonstrate greater limb asymmetry in sagittal plane knee joint mechanics compared to the HQ group and uninjured participants serving as a control group. The second hypothesis tested was that, in the ACLR group, QF strength deficits would estimate knee joint mechanics during landing after controlling for graft type, presence of meniscus injury, knee pain, and knee symptoms.

METHODS

Participants

A total of 124 participants between 14 and 25 yr of age were recruited from local orthopedic practices, physical therapy clinics, and from the community from 2007 to 2012 (Table 1). Seventy-seven individuals were recruited for the ACLR group. Participants were included in this group if they had a primary, unilateral ACL reconstruction, completed their rehabilitation program, were cleared for return to all high-level athletic activities by their surgeon and treating rehabilitation specialist, and intended return to cutting and pivoting sports on a regular basis ($\geq$50 h·yr^{-1}). Testing occurred within 4 wk of return-to-sport clearance. Neither rehabilitation nor the clearance decision for sports participation was controlled by the study. Before enrolling in the study, the decision for return-to-sports clearance was made by each participant's medical team, with or without the use of objective-based criteria. Individuals with all graft types (including bone–tendon–bone, hamstrings tendon, or allograft tissue grafts) and those with and without meniscus repair or partial meniscectomy at the time of ACL reconstruction were included. Individuals were excluded from testing if they

TABLE 1. Participant characteristics by quadriceps femoris strength group.

	HQ Group (n = 37)	LQ Group (n = 31)	CTRL Group (n = 47)	P
Age (yr)	17.4 (2.6)	17.6 (3.1)	17.0 (2.3)	0.62
Height (m)	1.68 (0.08)	1.70 (0.10)	1.67 (0.09)	0.55
Weight (kg)	64.9 (9.9)	73.1 (18.0)	62.5 (12.6)	0.004* LQ > HQ, P = 0.04 LQ > CTRL, P = 0.003
Sex, n				0.88
Female	26	20	32	
Male	11	11	15	
Graft type, n				<0.001*
PT BTB	9	22	—	
HS	25	6	—	
Allo	3	3	—	
Time from ACL reconstruction to testing (time of return to sport) (months)				0.39
Mean (SD)	8.4 (1.8)	8.0 (2.4)	—	
Range	5.6–15.0	2.9–15.1	—	

Data are means and SD unless otherwise indicated.
*Significance at $P < .05$.
Allo, allograft; CTRL, control group; HQ, individuals with anterior cruciate ligament reconstruction and a quadriceps index ≥90%; HS, hamstring tendon graft; LQ, individuals with anterior cruciate ligament reconstruction and a quadriceps index <85%; PT BTB, patellar tendon, bone–tendon–bone graft.

1) reported a history of low back or either lower extremity injury or surgery (beyond ACL injury) requiring the care of a physician in the past year, 2) sustained a concomitant ligament injury (beyond grade 1 medial collateral ligament injury) in the involved limb, or 3) had a modified ACL reconstruction procedure due to open epiphyseal plates in the tibia or femur. Most participants returned to competitive middle/high school or club sport teams (66%), followed by return to recreational sport teams (26%), and return to competitive collegiate teams (7%; level of sport not reported for one individual [1%]).

Forty-seven participants between 14 and 25 yr of age were recruited from the community to serve as a control group (CTRL group; Table 1). Individuals were included in the CTRL group if they reported no history of low back surgery or surgery in either lower extremity, had no history of injury requiring the care of a physician in the past year in the low back or either lower extremity, and reported regular participation (≥50 $h \cdot yr^{-1}$) in cutting and pivoting sports.

The involved, or test limb, was identified as the injured limb of the ACLR group; for the CTRL group, this was randomly assigned. All participants, and guardians when required, provided written consent and assent approved by the institutional review board. Participants included in this analysis are part of an ongoing, prospective study of outcomes after ACL reconstruction at Cincinnati Children's Hospital Medical Center, which approved the protocol for this study.

QF Isometric Strength Assessment

QF isometric strength was quantified with an isokinetic dynamometer (Biodex Medical Systems, Shirley, NY) during a maximum voluntary isometric contraction. This procedure has been used to quantify QF torque in individuals with ACL injury and reconstruction and yields reliable measurements (7,9,11,15,35). Participants were positioned in the dynamometer with the trunk fully supported, the hips flexed to approximately 90°, the knee flexed to 60°, and the knee joint line aligned with the dynamometer axis. The dynamometer resistance pad was secured to the anterior aspect of the distal shank, and the pelvis and thigh were stabilized with straps. After one practice trial, three recorded maximum effort trials (5 s in duration separated by 15 s of rest) were completed for each knee with real-time visual and verbal feedback provided. For the ACLR group, the uninvolved side was always tested first, and for the CTRL group, the order of testing was randomized. The peak torque obtained for each limb during the three trials was normalized to body weight (BW; $N \cdot m \cdot kg^{-1}$) and used for further analysis. Isometric QF peak torque values are routinely used to calculate asymmetry between the involved and uninvolved limbs (7,11,15,35). As such, the peak torque value for each limb was used to calculate the quadriceps index (QI) by dividing the peak torque value of the involved/test limb by the uninvolved/nontest limb and multiplying by 100%. As calculated, a QI of 100% indicates perfect strength symmetry between the two limbs and a QI of <100% indicates a strength deficit in the involved limb.

Subdivision of ACLR group. The ACLR group was subdivided into strength groups based on QI: high quadriceps group (HQ, QI ≥ 90%) and low quadriceps group (LQ, QI < 85%). Cutoff scores were based on our previous work in this population (34), research indicating that a side-to-side difference in peak QF force output of >10% is considered to reflect differences in the capacity of the muscle performance beyond measurement error (33) and commonly reported QF strength criterion values for return-to-sport decision making in the literature (12,30). The sample size estimate for this study was based on a prior pilot study evaluating differences in limb symmetry in performance-based measures of function between the HQ and LQ groups. On the basis of these data, a sample size of 22 participants per group was required to achieve a power of 0.80 with an α level of 0.05. Of the 77 participants in the ACLR group, 37 were in the HQ group, 31 were in the LQ group, and 9 had a QI between 85% and 89%. Group comparisons were only made between the HQ and LQ groups owing to the small group size of those with QI = 85%–89%.

All participants in the ACLR group ($n = 77$) were included in the regression analysis.

Measures of Knee Pain and Symptoms

To quantify knee pain and symptoms, participants completed the Knee Injury and Osteoarthritis Outcome Score (KOOS) (31). The KOOS covers five dimensions—pain, symptoms, activities of daily living, sport and recreation activities, and knee-related quality of life—that are scored as separate and independent subsets (31). The KOOS is a valid, reliable, and responsive measure (16,31). All five subsets were completed, but only the knee pain (KOOS-pain) and symptoms (KOOS-symptoms) subsets were used for hypothesis testing. The knee pain subset relates to the frequency and the amount of knee pain experienced during activities of daily living (including walking, twisting/pivoting, and negotiating stairs). The symptoms subset relates to the frequency of knee symptoms, such as swelling, grinding, catching, and stiffness. Each subset is scored independently and questions are scored on a 0–4 scale. Subset scores are transformed into a 0%–100% score, with 100% representing no knee problems.

Motion Analysis Protocol

Testing procedure. Three-dimensional motion analysis was used to calculate knee kinematic and kinetic patterns and ground reaction force data during a bilateral drop vertical jump (DVJ) maneuver. A 10-camera motion analysis system (Eagle cameras; Motion Analysis Corporation, Santa Rosa, CA) tracked the position of 37 retroreflective markers (240 Hz) secured to specific locations and anatomic landmarks of the bilateral feet, ankles, shanks, knees, thighs, pelvis, trunk, and upper extremities to determine joint centers and segment position, as well as to track segment motion during dynamic trials. For the DVJ trials, participants were positioned on the top of a 31-cm box and were instructed to drop off the box simultaneously with both feet, landing with each foot onto separate force platforms (AMTI, Watertown, MA), and then to perform a maximal effort vertical jump toward an overhead target. Each participant completed three usable trials. Data from each force platform (1200 Hz) were synchronized with the motion analysis system. These methods have been published previously (26) and we have demonstrated high reliability in obtaining variables of interest with these methods in individuals after ACL reconstruction (23,26).

Data management. Knee kinematic and kinetic variables of interest were calculated with Visual 3D (Version 4.0; C-Motion, Inc., Germantown, MD) and custom-written MATLAB (Version 7; The MathWorks, Inc., Natick, MA) software over the initial landing phase of the DVJ. Landing phase was defined from initial contact, when the vertical ground reaction force first exceeded 10 N, to the lowest point of the body's center of mass (26). During the landing phase, marker trajectories and force plate data used for joint moment calculations were filtered with a bidirectional low-pass fourth-order Butterworth digital filter (12-Hz cutoff frequency). In addition, force plate data used in calculating peak ground reaction force and loading rate were filtered with a bidirectional low-pass fourth-order Butterworth digital filter (100-Hz cutoff frequency). Kinematic variables of interest included peak knee flexion angle during landing, as well as the knee flexion excursion during the landing phase. Inverse dynamics were used to calculate sagittal plane knee moments from the kinematic and force plate data and were normalized by BW ($N \cdot m \cdot kg^{-1}$). Kinetic variables of interest included peak vertical ground reaction force (normalized to BW) during landing phase, loading rate (peak vertical ground reaction force divided by time to reach peak; BW per second) (5,23), as well as the peak external knee flexion moment during the landing phase. The mean of the normalized values for the involved/test and uninvolved/nontest limbs for the three DVJ trials were used to calculate limb symmetry values by dividing the involved/test limb value by the uninvolved/nontest limb value and multiplying by 100% to calculate a limb symmetry index (LSI) for each variable of interest.

Statistical Analysis

Statistical analyses were performed with IBM SPSS Statistics Version 19.0 (SPSS, Inc., Chicago, IL), and statistical significance was established *a priori* ($\alpha \leq 0.05$). To test the first hypothesis that the LQ group would demonstrate greater limb asymmetry in sagittal plane knee joint mechanics during the landing phase of the DVJ compared to the HQ and CTRL groups, multivariate analyses of covariance were performed. The independent variable of group (HQ vs LQ vs CTRL) and the dependent variables of kinematic and kinetic limb symmetry scores were entered into the model. Multivariate analyses of covariance were also performed on the normalized kinematic and kinetic variables of interest for the involved/test and uninvolved/nontest limbs. Participants' age and sex were entered as covariates for all analyses.

Linear regression analysis was used to test the second hypothesis that QF strength deficits would estimate knee mechanics during landing in the ACLR cohort after controlling for graft type, presence of meniscus injury, knee pain, and knee symptoms. Separate regressions were performed on knee kinematic and kinetic limb symmetry variables (dependent variables) that were found to be significantly different among the groups. The independent variables were determined *a priori* as those thought to be most influential on knee mechanics. Multicollinearity among the independent variables was checked with Pearson correlation analysis and variance inflation factors (<3), and it was determined that each independent variable could be entered into the regression models. For each regression, graft type, presence of meniscus injury, knee pain (KOOS-pain), and knee symptoms (KOOS-symptoms) were put into the model first. Then, QI was entered into the model to assess the influence of

QF strength on limb symmetry during landing after accounting for the influence of the other independent variables.

RESULTS

The participants in the HQ, LQ, and CTRL groups did not differ in terms of age ($P = 0.62$), height ($P = 0.55$), or time from surgery to return to sport (i.e., testing; $P = 0.39$; Table 1). On average, participants in the LQ group weighed more than the participants in the HQ ($P = 0.04$) and CTRL groups ($P = 0.003$; Table 1).

Overall, the LQ group demonstrated greater limb asymmetry in sagittal plane knee joint mechanics during the landing phase of the DVJ than did the HQ and CTRL groups. Significant differences were observed among the groups in terms of limb symmetry for peak external knee flexion moment ($P < 0.001$), peak vertical ground reaction force ($P < 0.001$), and peak loading rate ($P = 0.008$; Fig. 1). Pairwise comparisons showed that the LQ group demonstrated greater asymmetry in peak external knee flexion moments, peak vertical ground reaction force, and peak loading rates than the HQ ($P \leq 0.001$, $P < 0.001$, $P = 0.009$, respectively) and the CTRL ($P \leq 0.001$, $P < 0.001$, $P = 0.043$, respectively) groups (Fig. 1). There were no differences between the HQ and CTRL groups for any limb symmetry measures ($P > 0.05$; Fig. 1). In the LQ group, observed differences in limb symmetry are due to altered mechanics in both the involved and uninvolved limbs based between limb comparisons among the groups (Table 2). On the involved/test limb, pairwise comparisons showed that peak external knee flexion moment and peak vertical ground reaction force were lowest in the LQ group compared to the HQ ($P = 0.01$ and $P = 0.003$, respectively) and CTRL groups ($P < 0.001$ and $P < 0.001$, respectively), with no differences between the HQ and CTRL groups ($P > 0.05$, for all; Table 2). On the uninvolved/nontest limb, pairwise comparisons showed that peak loading rate was highest in the LQ group compared to the HQ ($P = 0.004$) and CTRL groups ($P = 0.002$; Table 2). For peak vertical ground reaction force, the uninvolved limb was higher in the LQ group than that in the HQ group ($P = 0.005$; Table 2). There were no differences in the uninvolved/nontest limb between the HQ and CTRL groups for all measures ($P > 0.05$, for all; Table 2).

In the entire ACLR cohort ($n = 77$), QF strength deficits estimated sagittal plane knee mechanics even after controlling for graft type, presence of meniscus injury, knee pain, and knee symptoms. For all models, QI was a unique and significant predictor of asymmetry during landing after taking into the account the influence of all the other independent variables (Table 3). In the final model for LSI-peak external knee flexion moment ($R^2 = 0.501$), graft type ($\beta = 0.295$, $P = 0.002$) and QI ($\beta = 0.510$, $P < 0.001$) were the only statistically significant predictors. In the final model for LSI-peak vertical ground reaction force ($R^2 = 0.274$), QI was the only significant predictor ($\beta = 0.412$, $P < 0.001$). Similar results were found for LSI-loading rate because QI was the only significant predictor in the final model ($R^2 = 0.152$, $\beta = 0.253$, $P = 0.04$).

DISCUSSION

The purpose of this study was to investigate the effect of QF strength asymmetry at the time of return to sport on

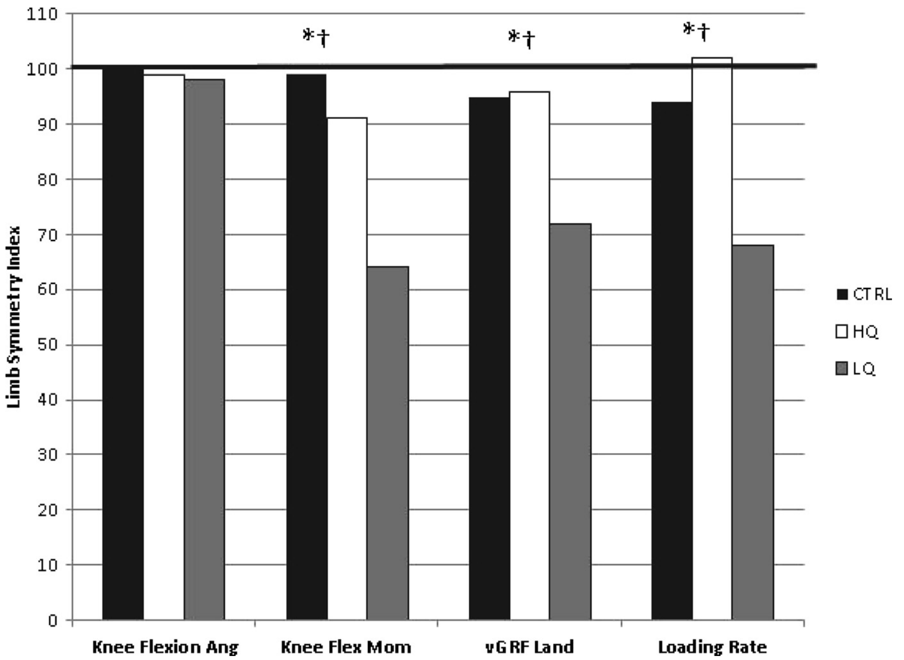

FIGURE 1—Limb symmetry for peak kinematic and kinetic variables of interest during landing between the strength groups (*LQ significantly less than HQ, †LQ significantly less than CTRL), with 100 indicating perfect symmetry between the involved/test and uninvolved/nontest limbs. Ang, angle; CTRL, control group; Flex Mom, external flexion moment; HQ, high quadriceps group; LQ, low quadriceps group; vGRF Land, peak vertical ground reaction force.

TABLE 2. Landing variables of interest by quadriceps femoris strength group.

	CTRL (*n* = 47)	HQ (*n* = 37)	LQ (*n* = 31)	*P*	*P*: Pairwise
Peak knee flexion (°)					
Inv	78.3 (8.1)	79.2 (8.5)	76.9 (8.6)	0.56	
Unv	77.8 (7.7)	80.4 (8.3)	78.4 (10.1)	0.29	
Knee excursion (°)					
Inv	58.7 (9.9)	60.9 (10.0)	59.6 (10.5)	0.48	
Unv	59. 6 (8.9)	62.4 (10.6)	61.5 (11.6)	0.33	
Peak knee flexion moment ($N \cdot m \cdot kg^{-1}$)					
Inv	2.0 (0.4)	1.8 (0.4)	1.4 (0.6)*,**	<0.001	*LQ < HQ, *P* = 0.01
Unv	2.0 (0.5)	2.0 (0.5)	2.3 (0.9)	0.13	**LQ < CTRL, *P* < 0.001
Peak vGRF (× BW)					
Inv	2.0 (0.4)	1.9 (0.4)	1.6 (0.3)*,**	<0.001	*LQ < HQ, *P* = 0.003
Unv	2.1 (0.4)	2.0 (0.3)	2.3 (0.5)***	0.007	**LQ < CTRL, *P* < 0.001 ***LQ > HQ, *P* = 0.005
Peak loading rate (× BW per second)					
Inv	11.3 (4.5)	11.5 (4.6)	10.2 (4.5)	0.48	*LQ > HQ, *P* = 0.004
Unv	12.5 (4.1)	13.0 (5.0)	16.8 (7.6)*,**	0.001	**LQ > CTRL, *P* = 0.002

Data are means and SD unless otherwise indicated.
BW, body weight; CTRL, control group; HQ, high quadriceps strength group with anterior cruciate ligament reconstruction; Inv, involved limb; LQ, low quadriceps strength group with anterior cruciate ligament reconstruction; LSI, limb symmetry index; Unv, uninvolved limb; vGRF, vertical ground reaction force.
*Significant difference between the LQ and HQ groups.
**Significant difference between the LQ and CTRL groups.
***Significant difference between the LQ and HQ groups.

movement patterns during a high-level bilateral landing maneuver in young athletes after ACL reconstruction (ACLR group). Testing was done at the time of return-to-sports participation, and to be eligible to participate, all participants in the ACLR group had been cleared for and intended return to unrestricted participation in cutting and pivoting sports. We confirmed our first hypothesis that individuals in the ACLR group with the largest QF strength deficits (LQ group) demonstrate greater asymmetry in sagittal plane knee joint mechanics during landing compared to those with ACLR and minimal QF strength deficits (HQ group) and uninjured individuals (CTRL). Specifically, participants in the LQ group demonstrated greater limb asymmetry in external knee flexion moments, peak vertical ground reaction force, and peak loading rate compared to those in the HQ and CTRL groups. On the involved limb, the LQ group demonstrated reduced external knee flexion moments and reduced peak vertical ground reaction force; whereas on the uninvolved limb, the LQ group demonstrated higher peak vertical ground reaction forces and peak loading rates compared to the HQ and CTRL groups. We also confirmed our hypothesis that QF strength deficits estimate sagittal plane knee mechanics even after controlling for the contributions of graft type, presence of meniscus injury, knee pain, and knee symptoms. To our knowledge, this is the first report evaluating QF strength impairments and knee mechanics during landing specifically at the time of return to sport in individuals after ACL reconstruction. Importantly, the results of this study indicate that deficits in QF strength at this time-point negatively affect knee joint mechanics during a bilateral athletic maneuver, which may have important implications on the QF strength criterion values appropriate for return-to-sport clinical decision making.

TABLE 3. Results of the linear regression analyses (ACLR group only, *n* = 77).

Dependent Variable	Independent Variable	R^2 Change	R^2	*P*
LSI-peak knee extension moment	Graft type			
	Meniscus injury	0.292		<0.001*
	Knee pain			
	Knee symptoms			
	QI	0.209		<0.001*
	Overall model		0.501	<0.001*
LSI-peak vGRF	Graft type			
	Meniscus injury	0.138		0.03*
	Knee pain			
	Knee symptoms			
	QI	0.137		<0.001*
	Overall model		0.274	<0.001*
LSI-loading rate	Graft type			
	Meniscus injury	0.100		0.10
	Knee pain			
	Knee symptoms			
	QI	0.052		0.04*
	Overall model		0.152	0.04*

*Significant R^2 change or R^2 value.
LSI, limb symmetry index; QI, quadriceps index; vGRF, vertical ground reaction force.

Our previous work in a similar cohort identified that QF strength deficits at the time of return to sport were common because 44% of our sample had >15% strength deficits compared to the uninjured limb (34). Further, we found that those with the largest QF strength deficits (synonymous with the LQ group) reported worse knee-related function and demonstrated the largest asymmetry in performance-based measures (i.e., single-leg hop tests) compared to those with minimal strength deficits (synonymous with the HQ group) and uninjured individuals (34). Taken together, the findings indicate that young, active individuals after ACL reconstruction with deficits in QF strength (LQ group) at the time of return to sports not only demonstrated reduced function and performance but also demonstrated altered knee mechanics during landing compared to those with nearly symmetrical QF strength (HQ group). These findings may have significant implications on the long-term joint integrity and risk of second ACL injury after ACL reconstruction.

Numerous studies show that reconstruction of the ACL alone does not protect against premature development of knee osteoarthritis. As early as 10–15 yr after ACL injury, the prevalence of knee osteoarthritis is as high as 62% in those with isolated injuries and 80% in those with concomitant injuries (21). After ACLR, QF strength deficits are theorized to be associated with the development of knee osteoarthritis by decreasing the ability of the QF to attenuate shock (14) and altering joint loading in a manner postulated to promote joint damage (4). The ability of the QF strength groups (HQ vs LQ) to discriminate differences in knee movement patterns, along with QF strength being a unique and significant predictor of these altered patterns, do indicate the likely role that QF muscle weakness plays in the altered joint mechanics in this patient population. Recently, the relationship between QF muscle strength and tibiofemoral joint space width was observed in a longitudinal cohort (36). Tourville et al. (36) observed that participants with significantly narrowed joint space width difference at 4 yr after ACL reconstruction had significant QF strength deficits soon after the injury that persisted over time compared with ACL reconstruction participants with normal joint space width difference and controls. Although the study by Tourville et al. (36) did not report on knee mechanics during dynamic activity, there is potential for an interaction between QF strength deficits, altered mechanics, and degenerative joint changes, which remains a focus of future work.

Rates of second injury are high after unilateral ACL reconstruction and typically occur within the first 7–12 months of returning to sports activities (13,24,26). Our previous prospective study identified biomechanical risk factors of second injury (26), of which limb asymmetries in sagittal plane knee moments during landing were a primary predictor. In the current study, we found that participants in the LQ group had larger asymmetry in external knee flexion moments while those with nearly symmetrical QF strength (HQ group) demonstrated knee kinetic patterns that are indistinguishable from uninjured individuals. Further, second ACL tears more frequently occur in the contralateral limb (24) and may be related to asymmetrical loading of the lower extremities. Asymmetries in vertical ground reaction forces and loading rates are noted at the time of return to sport (25) and for up to 2 yr after ACL reconstruction (23) during a bilateral landing. This compensation pattern involving increased loading of the uninvolved limb may put the contralateral limb at greater risk for subsequent injury. The current results show greater asymmetries in vertical ground reaction force and loading rates during landing in the LQ groups and, more specifically, show reduced involved limb peak vertical ground reaction forces and higher uninvolved peak vertical ground reaction force and loading rate compared to the HQ and uninjured groups. These findings potentially indicate that those with greater QF strength asymmetries (LQ group) show compensation patterns that put them at greater risk for further injury; however, further work is warranted in this area.

Our findings are consistent with previous studies that have identified kinematic and kinetic alterations in those with ACL reconstruction. After ACL reconstruction, altered knee joint mechanics are observed during lower-level (i.e., gait) (3,37) and higher-level (i.e., jogging, jumping, landing) (2,6,8,20,22,23,25) activities. Landing mechanics of the trunk, hip, and ankle joints may also show compensatory loading patterns in this population. In this study, we did not evaluate movement patterns in planes or joints beyond the sagittal plane mechanics of the knee, and this remains an area of our future analysis. Few previous studies have evaluated the relationships of QF strength to movement mechanics and, similar to our findings, have found significant relationships (2,15,20). In this study, the unique contribution of QF strength deficits on knee mechanics was specifically assessed with our regression analyses. Potential factors that could affect performance including graft type, presence of meniscus injury, knee pain, and knee symptoms were accounted for in the regression analysis. There are other factors that likely influence knee mechanics, and this is indicated in our results by the moderate R^2 values. It is also possible that evaluation of dynamic measures of QF muscle performance (i.e., isokinetic strength, isokinetic power) may offer further insight into the relationship of QF muscle performance with knee joint mechanics during dynamic tasks. Nonetheless, our results show that QI is a unique and significant predictor of limb symmetry in landing mechanics at the knee even after controlling for graft type, presence of meniscus injury, knee pain, and knee symptoms.

Most previous works in this area have evaluated movement patterns and strength deficits at specific time points from surgery (i.e., 3 wk, 8 wk, 12 wk, etc., after surgery). Recently, Oberlander et al. (20) evaluated the relationship between QF strength and a single-leg landing activity at 12 months after ACL reconstruction. To the best of our knowledge, this is the first study to evaluate the effect of QF strength deficits on movement mechanics at the time of return to sport. The decision of "return to sport" is a critical time point in the rehabilitation and medical decision-making process. Clearance for "return to sport" indicates the medical and rehabilitation team's confidence in the readiness of the individual to participate in activities that place a large and likely unanticipated demand on knee joint structures and musculature, mainly the QF muscles. While this study was not designed to specifically delineate a criterion value for QF strength and return to sport criteria, the results do indicate that isometric QF strength deficits of >15% negatively affect knee joint loading patterns during a bilateral landing activity. The long-term implications of these alterations remain a focus of our ongoing work in this population.

Study Limitations. QF muscle strength performance is a commonly used clinical criterion related to return to sport in individuals after ACL reconstruction. The importance of QF muscle performance in this patient population, and the absence of empirical information regarding clinical milestones for return to sport, prompted this study. There are many potential contributing factors beyond QF muscle strength that affect knee joint mechanics during landing that were not addressed in this study. A number of studies indicate the importance of hip and trunk muscle strength and activation on lower extremity control and knee biomechanics (20,26,28). We also did not analyze movement patterns of the trunk, hip, or ankle, which may influence knee mechanics (20). The study sample of young, active individuals was specifically chosen given the prevalence of ACL injury within this demographic. However, the results of this study provide insight into the effect of QF strength deficits on movement mechanics during a bilateral landing task, and consideration of the findings may be appropriate for a broader spectrum of individuals after ACL reconstruction when establishing return to activity or physical therapy discharge criteria. Consideration for the young, female athlete is appropriate because recent studies show sex differences in movement patterns and second injury after ACL reconstruction in young athletes (24,25). The ratio of females to males between the ACLR and CTRL groups in this study was not similar, but the sample size limited us from further analysis of the influence of sex on our study. In this analysis, we accounted for sex as a covariate in our statistical models; however, the influence of sex on strength and limb asymmetries after ACL reconstruction in young, active individuals remains a focus of our ongoing work.

CONCLUSIONS

In young, active individuals at the time of return to sport after ACL reconstruction, QF strength deficits are associated with altered knee mechanics during a bilateral landing and estimate knee joint mechanics during landing beyond the influences of graft type, meniscus injury, knee pain, or knee symptoms. Specifically, individuals with QF strength deficits >15% on the involved limb (QI < 85%) demonstrate movement asymmetries during landing, specifically related to reduced involved knee kinetic patterns and higher loading rates on the uninjured limb. Individuals with more symmetrical QF strength (QI ≥ 90%) demonstrate landing mechanics that are indistinguishable from uninjured individuals. Further investigation of the effect of QF strength deficits and altered landing mechanics, along with other potential contributing factors, on sport performance, re-injury, and long-term joint integrity, is warranted.

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