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Strength Asymmetry and Landing Mechanics at Return to Sport after ACL Reconstruction

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Abstract

Purpose—Evidence-based quadriceps femoris muscle (QF) strength guidelines for return to sport following anterior cruciate ligament (ACL) reconstruction are lacking. This study

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Conflicts of Interest

There are no Conflicts of Interest. The results of the present study do not constitute endorsement by ACSM.

investigated the impact of QF strength asymmetry on knee landing biomechanics at the time of return to sport following ACL reconstruction.

Methods—Seventy-seven individuals (17.4 years) at the time of return to sport following primary ACL reconstruction (ACLR group) and 47 uninjured control individuals (17.0 years) (CTRL group) participated. QF strength was assessed and Quadriceps Index calculated (QI = [involved strength/uninvolved strength]*100%). The ACLR group was sub-divided 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 with 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<.001), reduced involved limb (p=.003) and increased uninvolved limb (p=.005) peak vertical ground reaction forces, and higher uninvolved limb peak loading rates (p<.004). There were no differences in the landing patterns between the HQ and CTRL groups on any variable (p>.05). In the ACLR group, QF strength estimated limb symmetry during landing after controlling for graft type, meniscus injury, knee pain and symptoms.

Conclusion—At the time of return to sport, individuals post-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 following ACL reconstruction.

Keywords

anterior cruciate ligament reconstruction; quadriceps; weakness; landing; kinematics; kinetics

INTRODUCTION

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]. While an ACL reconstruction procedure is the standard of care for individuals who want to return to high-level activities, recent studies indicate these individuals may be at high-risk for poor outcome [13, 26]. Return to sport rates are relatively low following ACL reconstruction, with 63% resuming pre-injury 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 re-injury within the first 7 months following 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 limb loading strategies during squatting [19], jumping and landing activities [6, 8, 20, 22, 23, 25] that are consistently noted following 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. While 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 following 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]. While 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 greater than 15% negatively impact 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 impact 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 years following ACL reconstruction [2, 6, 8, 22, 23, 25] and are implicated in risk of second ACL injury [26] as well as risk of knee osteoarthritis [4, 14, 15]. Poor QF strength is implicated in abnormal movement patterns and asymmetrical limb loading strategies following ACL reconstruction [2, 15, 20]. QF strength accounts for a significant portion of the variance in sagittal plane knee angle and 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), while 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 weeks following surgery, with some individuals regularly participating in some activity (jogging, running, 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 following ACLR [20]. In this analysis, all study participants had returned to active sports participation 7–8 months prior to 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 impact 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 towards 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 impact of QF strength asymmetry at the time of return to sport on movement patterns during a high-level bilateral landing maneuver in young athletes following ACL reconstruction (ACLR group). For this analysis, the ACLR group was sub-divided into a High-Quadriceps (HQ) group (those with a QF strength deficit of 10% or less in the involved limb compared to the uninvolved limb) and a Low-Quadriceps (LQ) group (those with a QF strength deficit of greater than 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 years of age were recruited from local orthopaedic practices, physical therapy clinics, and from the community from 2007–2012 (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 (≥ 50 hours/year). Testing occurred within 4 weeks of return to sport clearance. Neither rehabilitation, nor the clearance decision for sports participation, were controlled by the study. Prior to 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 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 I 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 1 individual (1%).

Forty-seven participants between 14 and 25 years 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 hours/year) in cutting and pivoting sports.

The involved, or test limb, was identified as the injured limb of the ACLR group and for the CTRL group 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 following ACL reconstruction at Cincinnati Children's Hospital Medical Center.

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 anterior aspect of the distal shank and the pelvis and thigh were stabilized with straps. Following 1 practice trial, 3 recorded maximum effort trials (5 seconds in duration separated by 15 seconds 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 3 trials was normalized to body weight (Nm/kg) 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/non-test limb and multiplying by 100%. As calculated, a QI of 100% indicates perfect strength symmetry between the two limbs and a QI of less than 100% indicates a strength deficit in the involved limb.

Sub-division of ACLR group—The ACLR group was sub-divided 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 greater than 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. Based on these data, a sample size of 22 participants per group was required to achieve a power of 0.80 with an alpha 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 due 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 5 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 5 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 frequency and amount of knee pain experienced during activities of daily living (including walking, twisting/pivoting, 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 percent 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-centimeter 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 towards an overhead target. Each participant completed 3 usable trials. Data from each force platform (1200 Hz) was 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 following 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 Newtons, 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 bi-directional low-pass fourth-order Butterworth digital filter (12 Hz cutoff frequency). Additionally, force plate data used in calculations for peak ground reaction force and loading rate were filtered with a bi-directional 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 body weight (Nm/kg). Kinetic variables of interest included peak vertical ground reaction force (normalized to body weight (BW)) during landing phase, loading rate (peak vertical ground reaction force divided by time to reach peak; BW/seconds) [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/non-test limbs for the 3 DVJ trials were used to calculate limb symmetry values by dividing the involved/test limb value by the uninvolved/non-test 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* ($\alpha \leq .05$). 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 co-variance were performed. The independent variable of group (HQ versus LQ versus CTRL) and the dependent variables of kinematic and kinetic limb symmetry scores were entered into the model. Multivariate analyses of co-variance were also performed on the normalized kinematic and kinetic variables of interest for the involved/test and uninvolved/non-test limbs. Participant age and sex were entered as co-variates 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. Multi-collinearity 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=.62), height (p=.55), or time from surgery to return to sport (ie. testing) (p=.39) (Table 1). On average, the LQ group weighed more than the HQ (p=.04) and CTRL groups (p=.003) (Table 1). Overall, the LQ group demonstrated greater limb asymmetry in sagittal plane knee joint mechanics during the landing phase of the DVJ compared to the HQ and CTRL groups. Significant differences were observed among the groups in terms of limb symmetry for peak external knee flexion moment (p<.001), peak vertical ground reaction force (p<.001), and peak loading rate (p=.008) (Figure 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 compared to the HQ (p=<0.001, p<0.001, p=.009, respectively) and the CTRL (p=<0.001, p<0.001, p=.043, respectively) groups (Figure 1). There were no differences between the HQ and CTRL groups for any limb symmetry measures (p>.05) (Figure 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 group (p=.01 and p=.003, respectively) and CTRL group (p<.001 and p<.001, respectively), with no differences between the HQ and CTRL groups (p>.05, for all) (Table 2). On the uninvolved/non-test limb, pairwise comparisons showed that peak loading rate was highest in the LQ group compared to the HQ group (p=.004) and CTRL group (p=.002) (Table 2). For peak vertical ground reaction force, the uninvolved limb was higher in the LQ group compared to the HQ group (p=.005) (Table 2). There were no differences in the uninvolved/non-test limb between the HQ and CTRL groups for all measures (p>.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=.501), graft type (beta value=.295, p=.002) and QI (beta value=0.510, p<.001) were the only statistically significant predictors. In the final model for LSI-peak vertical ground reaction force (R^2=.274), QI was the only significant predictor (beta value=.412, p<.001). Similar results were found for LSI-loading rate as QI was the only significant predictor in the final model (R^2=.152; beta value=.253, p=.04).

DISCUSSION

The purpose of this study was to investigate the impact of QF strength asymmetry at the time of return to sport on movement patterns during a high-level bilateral landing maneuver in young athletes following ACL reconstruction (ACLR group). Testing was done at the time of return to sports participation, and in order 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, the LQ group demonstrated greater limb asymmetry in external knee flexion moments, peak vertical ground reaction force, and peak loading rate compared to those 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, while on the uninvolved limb 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 following ACL reconstruction. Importantly, the results of this study indicate that deficits in QF strength at this time-point negatively impact 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.

Our previous work in a similar cohort identified QF strength deficits at the time of return to sport were common, as 44% of our sample had >15% strength deficits compared to the uninjured limb [34]. Further, we found 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 (ie. 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 post-ACLR reconstruction with deficits in QF strength (LQ group) at the time of return to sports not only demonstrated reduced function and performance, but also demonstrate 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 following 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 years following ACL injury, prevalence of knee osteoarthritis is as high as 62% in those with isolated injuries and 80% in those with concomitant injuries [21]. Following 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 years after ACLR had significant QF strength deficits soon after the injury that persisted over time compared with ACLR participants with normal joint space width difference and controls. While 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 following 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 was a primary predictor. In the current study, we found that the LQ group had the 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 years following 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. Following ACL reconstruction, altered knee joint mechanics are observed during lower-level (i.e. gait) [3, 37] and higher-level (ie. 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 impact 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 (ie. 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 work in this area has evaluated movement patterns and strength deficits at specific time-points from surgery (ie. 3 weeks, 8 weeks, 12 weeks, etc post-surgery). Recently, Oberlander et al. [20] evaluated the relationship between QF strength and a single leg landing activity at 12 months following ACLR. To the best of our knowledge, this is the first study to evaluate the impact 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 greater than 15% negatively impact 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 following 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 impact 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 impact 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 following ACL reconstruction when establishing return to activity or physical therapy discharge criteria. Consideration for the young, female athlete is appropriate as recent studies show sex differences in movement patterns and second injury following 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 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 following 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 following 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 greater than 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 impact 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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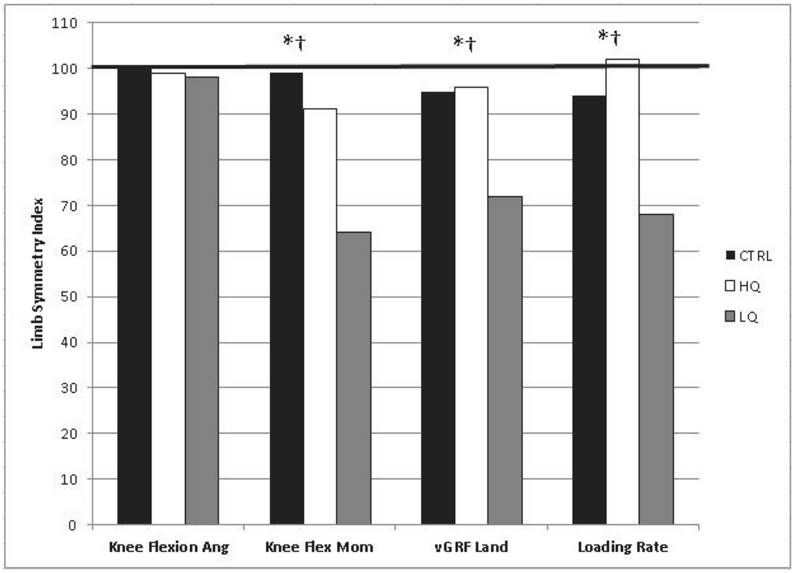

FIGURE 1.

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/non-test limbs. CTRL, control group; HQ, High Quadriceps group; LQ, Low Quadriceps group; Ang, angle; Flex Mom, external flexion moment; vGRF Land, peak vertical ground reaction force.

TABLE 1

Participant characteristics by quadriceps femoris strength group*.

	HQ group n=37	LQ group n=31	CTRL group n=47	P-value
Age (years)	17.4 (2.6)	17.6 (3.1)	17.0 (2.3)	.62
Height (m)	1.68 (0.08)	1.70 (0.10)	1.67 (0.09)	.55
Weight (kg)	64.9 (9.9)	73.1 (18.0)	62.5 (12.6)	.004** LQ>HQ, p=.04 LQ>CTRL, p=.003
Sex (n)				.88
Female	26	20	32	
Male	11	11	15	
Graft type (n)			-	<.001**
PT BTB	9	22		
HS	25	6		
Allo	3	3		
Time from ACL reconstruction to testing (time of return to sport) (months)	8.4 (1.8) Range: 5.6–15.0	8.0 (2.4) Range: 2.9–15.1	-	.39

*Data are means and standard deviations unless otherwise indicated,

**significance at p<.05.

Allo, allograft; CTRL, control group; HS, hamstring tendon graft; HQ, individuals with anterior cruciate ligament reconstruction and a quadriceps index higher or equal to 90%; LQ, individuals with anterior cruciate ligament reconstruction and a quadriceps index less than 85%; PT BTB, patellar tendon, bone-tendon-bone graft

TABLE 2

Landing variables of interest for by quadriceps femoris strength group.*

	CTRL n=47	HQ n=37	LQ n=31	P-value	P-value: pairwise
Peak knee flexion (°)					
Inv	78.3 (8.1)	79.2 (8.5)	76.9 (8.6)	.56	
Unv	77.8 (7.7)	80.4 (8.3)	78.4 (10.1)	.29	
Knee Excursion (°)					
Inv	58.7 (9.9)	60.9 (10.0)	59.6 (10.5)	.48	
Unv	59. 6 (8.9)	62.4 (10.6)	61.5 (11.6)	.33	
Peak knee flexion moment (Nm/kg)					
Inv	2.0 (.4)	1.8 (.4)	1.4 (.6) *†	<.001	* LQ<HQ, p=.01
Unv	2.0 (.5)	2.0 (.5)	2.3 (.9)	.13	†LQ<CTRL, p<.001
Peak vGRF (x BW)					
Inv	2.0 (.4)	1.9 (.4)	1.6 (.3) *†	<.001	* LQ<HQ, p=.003
Unv	2.1 (.4)	2.0 (.3)	2.3 (.5) ‡	.007	†LQ<CTRL, p<.001 ‡LQ>HQ, p=.005
Peak loading rate (x BW/s)					
Inv	11.3 (4.5)	11.5 (4.6)	10.2 (4.5)	.48	* LQ>HQ, p=.004
Unv	12.5 (4.1)	13.0 (5.0)	16.8 (7.6) *†	.001	†LQ>CTRL, p=.002

* Data are means and standard deviations unless otherwise indicated.

Abbreviations: CTRL, control group; HQ, high quadriceps strength group with anterior cruciate ligament reconstruction; LQ, low quadriceps strength group with anterior cruciate ligament reconstruction; Inv, Involved limb; Unv, uninvolved limb; vGRF, vertical ground reaction force; BW, body weight; LSI, limb symmetry index; N, Newtons; m, meters; kg, kilogram; s, seconds

TABLE 3

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

Dependent Variable	Independent variable	R^2 change	R^2 value	P-value
LSI-peak knee extension moment	Graft type Meniscus injury Knee pain Knee symptoms	.292		<.001*
	QI	.209		<.001*
	Overall model		.501	<.001*
LSI-peak vGRF	Graft type Meniscus injury Knee pain Knee symptoms	.138		.03*
	QI	.137		<.001*
	Overall model		.274	<.001*
LSI-loading rate	Graft type Meniscus injury Knee pain Knee symptoms	.100		.10
	QI	.052		.04*
	Overall model		.152	.04*

*indicates significant R^2 change or R^2 value. LSI, limb symmetry index; vGRF, vertical ground reaction force, QI, Quadriceps Index