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Comparison of Limb Loading Characteristics and Subjective Functional Outcomes Between Sexes After Anterior Cruciate Ligament Reconstruction

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Context: Anterior cruciate ligament reconstruction (ACLR) patients commonly adopt poor movement patterns that potentially place them at an increased risk for reinjury if untreated. Limb loading characteristics during functional tasks can highlight movement compensations.

Objective: To examine loading symmetry during a bilateral bodyweight squatting task between sexes, compare loading metrics between limbs and sexes, and describe the relationship between loading metrics and patient-reported outcomes (PROs) after ACLR.

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: One hundred forty-two patients (71 male, 71 female, age = 24.4 ± 11.10 years) with a primary, unilateral, uncomplicated ACLR completed a squatting assessment and PRO measures at approximately 5.2 months post-ACLR.

Main Outcome Measure(s): Normalized limb loading peak force (N/kg) and unilateral cumulative load (%) were collected bilaterally during the squatting task. Limb symmetry index (%) was calculated for normalized peak force. First, we compared limb loading symmetry (%) between sexes using an independent-samples *t* test. Second, we assessed differences in limb loading metrics between limbs and sexes via an analysis of covariance. Third, we used Spearman ρ correlations to determine the relationship between limb loading metrics and PROs.

Results: The majority of individuals (91 of 142, 64.1%) offloaded their ACLR limb (ACLR = 6.6 ± 1.56 N/kg, contralateral = 7.3 ± 1.61 N/kg, $P < .001$). Females significantly offloaded their ACLR limb (ACLR = 6.3 ± 1.38 N/kg, contralateral = 7.2 ± 1.62 N/kg, $P < .001$) whereas males did not significantly offload their ACLR limb (ACLR = 6.98 ± 1.65 N/kg, contralateral = 7.4 ± 1.60 N/kg, $P = .07$). Weak relationships were observed (P value range: −.23 to .19) across limb loading metrics and PROs.

Conclusions: Individuals approximately 5 months after ACLR, on average, offloaded their ACLR limb compared with the contralateral limb. Patients' tendency to offload their weight during a squat was influenced by sex. Relationships between limb loading metrics and PROs indicate patients who load their limbs disproportionately have a lower perception of their capability to complete activities of daily living and lower subjective knee function.

Key Words: bilateral squat, offloading, rehabilitation, return to activity

Key Points

- Patients approximately 5 months post–anterior cruciate ligament reconstruction (ACLR) offload their surgical limb compared with their contralateral limb during a bilateral squatting task.
- Females offloaded their ACLR limb more than their male counterparts during a bilateral squatting task at approximately 5 months post-ACLR.
- After an ACLR, patients who unevenly distribute their bodyweight across their surgical and contralateral limbs during a bilateral squat have a lower perception of their ability to complete activities of daily living.

Injury to the anterior cruciate ligament (ACL) is one of the most common musculoskeletal injuries, and subsequent surgical ACL reconstruction (ACLR) is the typical treatment within the United States.[1] After surgical intervention, many individuals struggle to return to preinjury levels of physical activity, with approximately 35% of athletes not able to return to their previous sport; for those who are able to return to their previous sporting activity, 45% are not able to return to competitive sport after ACLR.[2] Physical and psychological barriers can contribute to a person's ability to successfully return to activity (RTA).[1,3]

After ACLR, individuals may also have altered biomechanics during landing and walking.[4–6] The quality of movement can be compromised due to an unconscious offloading (ie, putting less of the patient's body mass on 1 foot compared with the contralateral side) of the ACLR limb compared with the contralateral limb.[7] Determining a patient's capacity to evenly distribute their weight across limbs during a functional task is critical for tailoring an optimal rehabilitation intervention after ACLR. If maladaptive offloading patterns from the ACLR limb to the contralateral limb persist throughout rehabilitation, it could exacerbate poor movement patterns during high-risk ballistic activities (ie, jumping), potentially increasing the risk of reinjury to the ipsilateral or contralateral ACL.[8]

Movement compensations after ACLR are commonly observed in patients and can be assessed with a variety of techniques.[9,10] The gold standard of movement pattern assessment is through the use of 3D motion-capture equipment, which can be costly and time-consuming.[10] A bilateral bodyweight squat is a movement that is simple, safe, low impact, low cost, and easily replicable.[9] Previous researchers who have assessed patients' limb loading characteristics during squatting tasks have distinguished a singular time point (ie, peak vertical ground reaction force) during the task that is used for analysis.[8,9] Although there is utility in investigating this discrete variable occurring at a singular time point, investigating cumulative loading characteristics throughout a squatting task could be a valuable addition to create a more comprehensive assessment of patients' movement patterns.[11,12]

Bilateral bodyweight squats are used during a multitude of activities of daily living (ADLs) and are modifiable throughout rehabilitation (eg, adding an external weight, increasing sets and repetitions, increasing tempo) to increase the task demands on patients.[9] Once performed correctly, they may be used to develop optimal motor patterns that can be transferred to more intensive skills or activities (eg, jump landings).[13,14] To date, a dearth of reports exist related to limb loading differences during a bilateral squat between sexes. However, previous researchers observed that females produced higher knee adduction moments, worse quadricep-to-hamstring muscle activity, and greater ACL limb forces and strains respectively compared with their male counterparts during gait, jump-cut maneuvers, and hopping assessments.[15–17] It is currently unknown as to whether there are differences in limb loading characteristics between sexes during a bilateral bodyweight squat after ACLR. If differences do exist between sexes, this could inform clinical decision-making to provide better personalized care but also highlight potential areas of focus during RTA assessments.

Psychological barriers are also an aspect of recovery that patients must overcome after ACLR that can influence patients' physical outcomes and their ability to successfully RTA to the same preinjury level of rigor.[18,19] Previous researchers have highlighted that psychological factors such as fear of injury or kinesiophobia, setting expectations, motivation, sports confidence, and optimism can be predictive of self-reported function such as pain, functional task performance, and the ability to successfully RTA.[1,19–21] Decreased sport-related confidence, as measured by the ACL–Return to Sport After Injury questionnaire, has been associated with decreased hop distance, decreased knee extension moment symmetry during jump landings, and decreased gait symmetry.[22–24] Prior authors have found that patients who adopt poor movement patterns, such as offloading their ACLR limb compared with the contralateral limb during gait, reported worse subjective knee function and symptoms.[25,26] It is unclear whether that relationship remains when investigating limb loading during a bilateral bodyweight squat and patient-reported outcomes (PROs).

The ability to use a safe and easily implementable task to determine how patients are loading their limbs throughout rehabilitation after ACLR allows clinicians to intervene and personalize patients' rehabilitation protocol based on their specific needs. Therefore, our aims were to (1) initially examine limb loading symmetry during a bilateral bodyweight squatting task between sexes, (2) compare limb loading metrics between limbs and sexes, and (3) assess the relationship between limb loading metrics and subjective function described through PROs in patients less than 9 months post-ACLR. We hypothesized that females would exhibit more asymmetric loading during the bilateral squatting task compared with their male counterparts and that patients would have asymmetric loading during the squatting task as indicated by an offloading of the ACLR limb compared with the contralateral limb. Additionally, we hypothesized that patients who had more symmetric loading during the squatting task would also have greater subjective knee function and psychological readiness to RTA and would report participation in higher levels of physical activity.

METHODS

Study Design

This observational cohort study was a part of a larger point-of-care, collaborative research program in a single academic health system. Our study was conducted in a controlled university laboratory setting and approved by the university's institutional review board for health science research. For our initial aim, the independent variable was sex (male versus female), and the dependent variable was normalized peak force limb symmetry index (LSI). For our second aim, the independent variables were limb (ACLR versus contralateral) and sex (male versus female), and the dependent variables were normalized peak force (N/kg) and unilateral cumulative load (UCL) expressed as a percentage.[7] For our third aim, the variables of interest were the scores from the PRO measures, normalized peak force (N/kg), UCL (%), and the absolute value of LSI that was calculated from normalized peak force recorded during the bilateral bodyweight squat. Sample size was based on identifying sex differences in limb loading using data collected in our lab as a variability estimate in limb loading. We determined that 104 (52 male and 52 female) patients were necessary to identify a moderate effect (Cohen $d = 0.50$) between sexes with an $\alpha \leq .05$ and power $(1 - \beta)$ of .80.

Participants

A total of 142 patients (50% female) volunteered to participate and were enrolled after providing written informed consent (Table 1). All patients attended their study session before clearance to RTA by their orthopaedic surgeon. We included patients if they had a primary, uncomplicated, unilateral, isolated ACLR. We excluded patients if they had a history of prior ACLR, multiligament reconstruction, contralateral ACL injury, or graft failure; had sustained other

Table 1. Participant Demographics

	Total Participants	Males	Females
Sample, No.	142	71	71
Age, mean ± SD, y	24.42 ± 11.09	23.83 ± 9.66	25.02 ± 12.39
Mass, mean ± SD, kg	78.28 ± 17.53	84.40 ± 17.79	72.16 ± 15.07[a]
Height, mean ± SD, cm	172.83 ± 10.01	178.41 ± 8.56	167.25 ± 8.09[a]
Time postsurgery, mean ± SD, mo	5.17 ± 1.40	5.03 ± 1.35	5.32 ± 1.44
Surgical limb = dominant limb, No. (%)[b]	58 (40.8)	33 (46.5)	25 (35.2)
Surgical limb = nondominant limb, No. (%)[b]	84 (59.2)	38 (53.5)	46 (64.8)
Graft type, No. (%)[b]			
Patella tendon	113 (79.6)	57 (80.3)	56 (78.9)
Hamstring tendon	17 (12)	7 (9.9)	10 (14.1)
Quadriceps tendon	11 (7.7)	7 (9.9)	4 (5.6)
Allograft	1 (0.7)	0 (0)	1 (1.4)

[a] Significantly lower values than males determined by an independent-samples *t* test ($P < .01$).
[b] Limb dominance and graft type are listed as the number of participants followed by the cumulative percentage.

lower extremity injuries or concussions within 6 months of study participation or at any time throughout the study; or had a history of neurological disorders.

Procedures

We measured limb loading during a bilateral bodyweight squat and PRO scores during a single visit. Limb dominance was also recorded and self-defined as the limb that a patient preferred using when kicking a soccer ball.

Bodyweight Squatting Task

Before starting data collection, patients were instructed to perform a standardized calibration protocol from the manufacturer. Patients were weighed, stood atop a pressure mat (SB Mat; Tekscan Inc), and then their mass was converted from arbitrary units to newtons. Once the pressure mat was calibrated to the patient's mass, we instructed patients to complete 3 sets of 3 repetitions of a squatting task with 30 seconds of rest between trials. To complete the squatting task, we instructed patients to stand with their feet shoulder-width apart and to perform a squat with approximately 90° of knee flexion or to the "height of a chair" and to return to their upright standing position (Figure 1) at a pace set by a metronome (40 beats per minute, in which patients were to be at maximum knee flexion at the bottom of the squat or at maximum knee extension at the top of the squat for each beep of the metronome). We provided patients with the opportunity to practice the squatting protocol until they felt comfortable performing the task. Vertical force was continuously measured from each limb independently using a pressure mat (SB Mat) and software (v 7.10-14; FootMat Research) sampled at 60 Hz during data collection.

Patient-Reported Outcomes

Participants also completed a series of PRO measures during the visit. The International Knee Documentation Committee Subjective Knee Form (IKDC) was recorded, determining subjective knee function.[27] The Knee Injury and Osteoarthritis

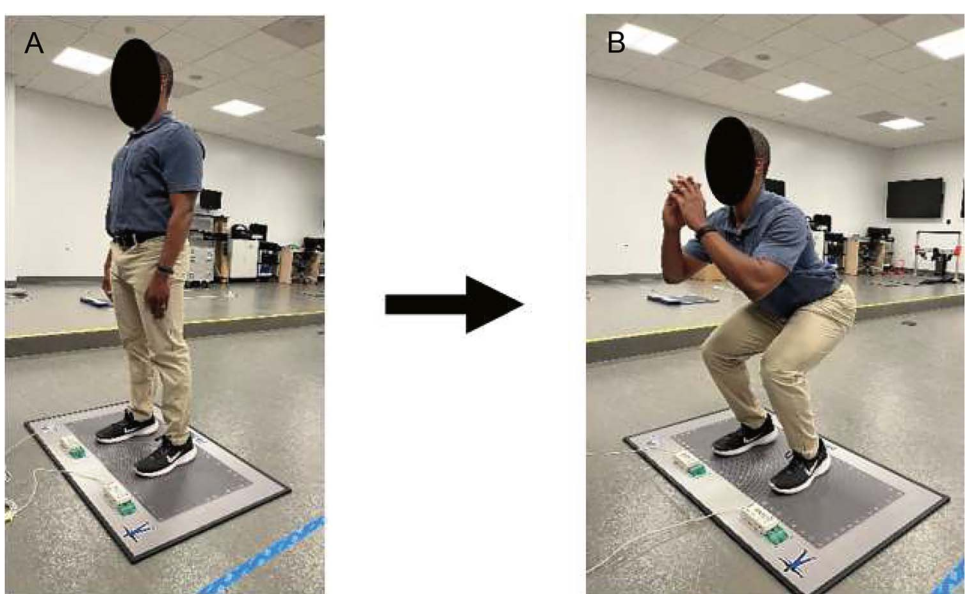

Figure 1. Data collection setup during the bilateral squatting task. Patients were instructed to squat to approximately the height of a chair then return to their starting position 3 consecutive times to the rhythm of a metronome set to 40 beats per minute. This was repeated across 3 trials.

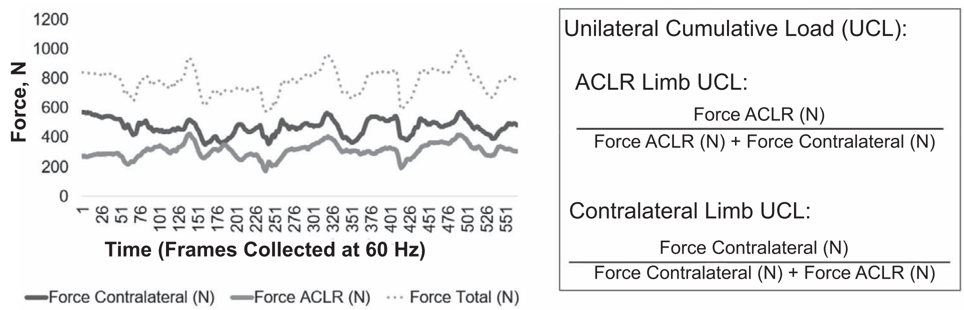

Figure 2. Unilateral cumulative load (UCL) calculation example. The graph to the left depicts a squatting trial of 3 bilateral bodyweight squat repetitions. The bold dark gray line represents the loading contribution from the contralateral limb, and the bold light gray line represents the loading contribution from the anterior cruciate ligament reconstruction (ACLR) limb. The dotted gray line is the summation of the ACLR and contralateral limbs creating a total force line representation. The box to the right indicates the equations used to calculate the ACLR UCL and contralateral UCL metric values.

Outcome Score (KOOS; subscales include Symptom, Pain, ADLs, Sport, and Quality of Life) assessed the severity of the knee symptoms and functional disabilities experienced by the patient.[28] The Anterior Cruciate Ligament Return to Sport After Injury (ACL-RSI) was collected to assess the patient's confidence, risk appraisal, and emotions related to resuming sport-related activities.[29] The Tegner Activity Scale (TAS) was recorded to determine patients' perceived activity level preinjury and in their current state during their lab visit based on work and sports activities.[30] All PRO measures have been found to be valid and reliable measures of their respective constructs.[27–31]

Data Processing

All data were processed using a custom MATLAB code (v 9.12.0, MATLAB R2022a; The MathWorks Inc).

Peak Force. We calculated peak force (N) individually for each limb by recording the largest single force output over each of the 3 sets, and then the average of those values across the 3 sets was calculated. Once the peak load was calculated, we then normalized to each patient's body mass (N/kg).

Unilateral Cumulative Load. The UCL is a novel measure that signifies the overall loading contribution of each limb throughout the entire squat trial. We calculated UCL as a percentage of each individual limb's vertical force production throughout the squat trial, then averaged across the 3 squatting trials. Figure 2 is an example of how the UCL was obtained. The bold light gray line representing the ACLR limb indicates lower force values compared with the bold dark gray line representing the contralateral limb. Therefore, the UCL for the ACLR limb for this trial would be smaller than the UCL of the contralateral limb. If the force lines from each limb were perfectly positioned on top of each other, this would indicate a UCL of 50%. Stated again, a UCL of 50% would mean that each limb is contributing the same amount of force throughout the trial and that the patient is equally distributing their body mass between the ACLR and contralateral limbs.

Limb Symmetry Index. We calculated LSI by dividing the peak force produced by the ACLR limb by that of the contralateral limb as a percentage, then averaged across the 3 trials. An LSI value of 100% is indicative of the ACLR limb producing the same or equal peak force value as the contralateral limb. We then calculated the absolute value of the LSI by conducting $1 - |LSI_{PeakForce}|$. An absolute value LSI score of 0 is indicative of equal (symmetrical) peak force from each limb. An absolute value LSI score greater than zero is indicative of higher peak force LSI from the ACLR limb, indicating the patient places more of their body mass on their ACLR limb during the squatting task. An absolute value LSI score less than zero is indicative of higher loading contributions from the contralateral limb, indicating the patient is offloading their ACLR limb by putting more of their body mass on their contralateral limb during the squatting task.

Statistical Analysis

An initial analysis was conducted using an independent-samples *t* test to compare normalized limb loading peak force LSI between males and females. For our second analysis, we evaluated the influence of sex on bilateral loading during squat tasks using a 2×2 (limb-by-sex) analysis of covariance while covarying for limb dominance (ie, whether the surgical limb was self-identified as the dominant or nondominant limb). Post hoc *t* tests were performed as appropriate. We conducted paired-samples *t* tests to compare normalized peak force limb loading values and UCL values between females and males and between the ACLR and contralateral limbs. We calculated and used Cohen *d* effect sizes to interpret pooled standardized mean differences, which are representative of the magnitude of observed differences. We classified effect size values as *small*, $\leq$0.29; *weak*, 0.30–0.49; *moderate*; 0.50–0.79; or *strong*, $>$0.80.[32]

The PRO data did not meet the assumptions of a normally distributed dataset; therefore, for our third analysis, we evaluated the relationship between PROs and limb loading metrics using a Spearman ρ correlation coefficient. We interpreted correlation coefficients as *weak*, $\leq$0.35; *moderate*, 0.36–0.67; or *strong*, 0.68–1.00.[33] Positive correlations indicate that, as an individual increases their limb loading or symmetry value, their PRO measures also improve. Negative correlations indicate that, as an individual offloads their limb or decreases their limb symmetry, their PRO outcomes improve. Ceiling or floor effects were evaluated and considered present if more than 15% of patients reported the best (ceiling) or worst (floor) possible score for each PRO.[34,35]

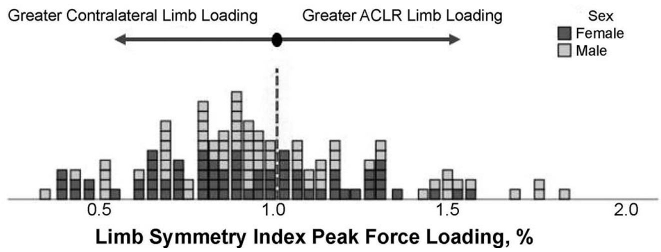

Figure 3. Limb symmetry index (LSI) frequency distribution. The dashed line represents the split between individuals who had an LSI value greater than or equal to 1.0 (n = 51) and less than 1.0 (n = 91). LSI ≥ 1.0: males, n = 25; females, n = 26; LSI < 1.0: males, n = 46; females, n = 45. Abbreviation: ACLR, anterior cruciate ligament reconstruction.

We used SPSS (v 28.0; IBM SPSS) for all statistical calculations. All analyses were performed with $\alpha \leq .05$ determined a priori.

RESULTS

Of our 142 participants, 91 (64.1%) exhibited peak force LSI values less than 1.0, which would indicate the majority of participants, who were on average 5.2 months postsurgery, were offloading their ACLR limb. For those individuals who had an LSI value less than 1.0, the mean ± SD LSI value for peak force was 76.8% ± 17.1%. Fifty-one individuals (35.9%) had an LSI value for peak loading greater than or equal to 1.0, indicating greater loading of the ACLR limb compared with the contralateral limb during the squatting task (Figure 3). Of our 51 individuals who exhibited an LSI value greater than or equal to 1.0, the mean ± SD LSI value for peak force was 127.3% ± 21.4%. Across males, 25 individuals (35.2%) had an LSI value greater than or equal to 1, and 46 (64.8%) had an LSI value less than 1.0. For females, 26 (36.6%) had an LSI value greater than or equal to 1.0, whereas 45 (63.4%) had an LSI value less than 1.0. We observed no significant differences between male and female peak force LSI values ($t = 1.54$, $P = .06$, Cohen $d = 0.26$; males, $\overline{X} = 0.99$, $\sigma = 0.33$; females, $\overline{X} = 0.91$, $\sigma = 0.28$).

We observed a significant limb-by-sex interaction for normalized limb loading peak force ($F_{1,139} = 5.71$, $P = .02$; Figure 4). Post hoc analysis revealed females offloaded their ACLR limb compared with their contralateral limb ($t = 3.55$, $P < .001$, Cohen $d = 0.42$; Table 2). Males, in general, offloaded their ACLR limb compared with their contralateral limb to a lesser extent than females ($t = 1.49$, $P = .07$, Cohen $d = 0.18$; Table 2).

We did not observe a limb-by-sex interaction for UCL ($F_{1,139} = 2.48$, $P = .12$). However, there was a main effect for limb, wherein the UCL of the ACLR limb (48.8% ± 10.0%) was loaded significantly less than the contralateral limb (51.2% ± 9.0%; $F_{1,139} = 11.84$, $P < .001$, Cohen $d = 0.22$). There was no difference in UCL across sexes ($F_{1,139} = 0.032$, $P = .86$).

Descriptive statistics for limb loading metrics and all PRO measures are found in Table 3. We observed weak significant negative relationships between the contralateral limb for normalized limb loading peak force and UCL and PROs ($P < .05$; Table 4). There were weak significant positive relationships between the ACLR limb for normalized limb loading peak force and UCL and PROs ($P < .05$; Table 4). Ceiling effects, defined as >15% of patients scoring the best possible score, were observed for only the following PRO measures: KOOS Pain (18.3% of patients scored 100), KOOS ADLs (36.6% of patients scored 100), KOOS Sport (15.5% of patients scored 100), and TAS preinjury (22.5% of patients scored a 10). No floor effects were observed for any PRO measures.

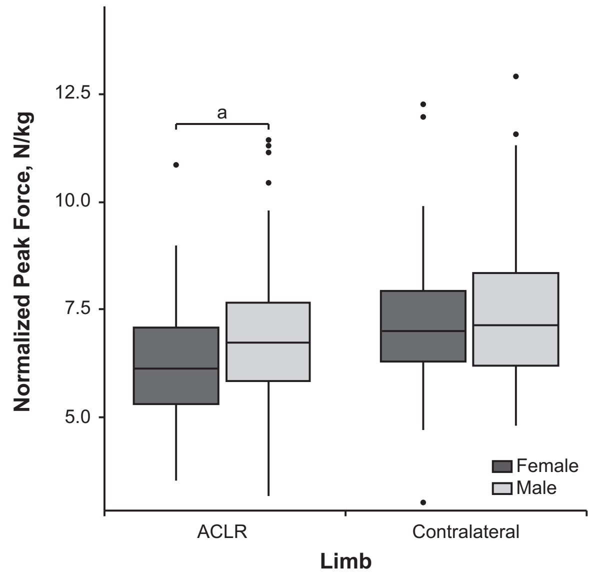

Figure 4. Limb loading normalized peak force differences between males and females after anterior cruciate ligament reconstruction (ACLR). [a] Significant difference between males and females (*P* < .05).

DISCUSSION

The purpose of our study was to examine limb loading symmetry during a bilateral bodyweight squatting task between sexes, compare side-to-side limb loading metrics between sexes, and explore the presence of a relationship with perceived function in patients recovering from unilateral ACLR. We observed that patients approximately 5 months post-ACLR, on average, offloaded their ACLR limb compared with their contralateral limb and that females offloaded their ACLR limb more than males during the bilateral bodyweight squatting task. Our findings align with previously conducted studies in which patients after ACLR offloaded their surgical limb compared with their contralateral limb during tasks such as a sit-to-stand, squat, and stop jump.[8,9,36] Our study builds upon previous findings by highlighting a unique offloading adaptation from females after ACLR compared with their male counterparts. Our findings could provide clinicians insights into how to optimize or potentially better tailor their patients' rehabilitation protocol based on their patients' sex.

The differences in our findings for the normalized peak force and UCL metrics were unexpected. Our hypothesis was that there would be significant difference across both metrics. However, there were significant differences for the normalized peak force metric and no significant differences for the UCL metric (Table 2). These results indicate that it is possible that the differences between limb loading metrics may be exaggerated when looking at a singular time point such as a single peak. The UCL metric, though not

Table 2. Limb Loading Metrics Across Limbs and Sexes (N = 142)

	ACLR	Contralateral	Effect Size, Cohen *d*	*P* Value	95% CI
Normalized peak force, N/kg					
Male	7.0 ± 1.65	7.4 ± 1.60	0.18	.07	−0.41, 0.06
Female	6.3 ± 1.38	7.2 ± 1.62	0.42	<.001[a]	−0.66, −0.18
Combined	6.6 ± 1.56	7.3 ± 1.61	0.31	<.001[a]	0.14, 0.47
UCL, %					
Male	49.3 ± 10.0	50.7 ± 9.5	0.07	.272	−0.31, 0.16
Female	48.4 ± 9.1	51.6 ± 9.1	0.18	.07	−0.42, 0.05
Combined	48.8 ± 9.28	51.2 ± 9.28	0.13	.06	−0.04, 0.29

Abbreviations: ACLR, anterior cruciate ligament reconstruction; UCL, unilateral cumulative load.
[a] Indicates significant differences between the ACLR and contralateral limbs ($P < .05$).

statistically significant in this sample, demonstrated patients' tendency to offload their ACLR limb compared with their contralateral limb with a small effect size (Table 2). The UCL metric is a unique comprehensive measure that allows for analysis in differences across all parts of the squatting trial, whereas the peak force metric is only a single moment in time. The lack of significance in the UCL metric potentially indicates that not all phases of the bilateral squat are asymmetric. It is also possible that the UCL metric may indicate that the variation in side-to-side loading or patients shifting their weight may be accounting for the variation in the time-course data. More research needs to be done with motion-capture analysis to determine which phases of the squat patients are offloading their ACLR limb.

We also observed that patients, on average, offloaded their ACLR limb compared with their contralateral limb during a bilateral squatting task, which aligns with previously conducted research.[7–9,36] The magnitudes of differences between limb loading discrepancies for the ACLR versus the contralateral limb in previously conducted studies were larger than the ones observed in this study.[7–9,36] This difference in magnitude could be due to differences in bilateral bodyweight squatting methodologies (eg, metronome use, tactile feedback, repetition scheme) and instrumentation (eg, motion capture, force plates, standardized footwear); however, the results are in congruence. Even though there was a difference in the magnitude of differences found compared with previous studies, patients participating in the current study were instructed to complete an inherently symmetric task, yet they still executed the task asymmetrically. The offloading from the ACLR limb observed in individuals during an easy and safe bilateral squatting activity is cause for concern. If this movement pattern adaptation is not corrected, this could perpetuate long-term when patients are participating in more dynamic and ballistic activities like running, jumping, and cutting maneuvers.[6,37] Poor biomechanics, specifically offloading the ACL limb, during these high-demand activities could increase one's risk for reinjury, and, when compounded over time, could catalyze the progression toward the development of early onset knee osteoarthritis.[4,8,38]

It is also important to note that 51 of the 142 participants (36%) had an LSI value of 1.0 or greater. It is currently unclear which physical or psychological characteristics these patients might have had that allowed them to evenly distribute or overload their ACLR limb during this squatting task. Authors of a recent study found that under 3 conditions, natural, instructed, and feedback, patients after ACLR went from being asymmetric in their loading during the natural condition to symmetrically loaded with the instructed and feedback conditions.[7] This finding indicates that, with the proper training and instruction, individuals after ACLR can evenly distribute their weight across their limbs. Authors of another previously conducted study found that time was a factor contributing to loading distribution: individuals who were >24 months post-ACLR overloaded their surgical limb compared with their contralateral limb.[27] One additional possible explanation could be that the patients in the current study were in a controlled laboratory setting doing a variety of lower extremity assessments on their surgical limb that could potentially have altered their focus during the task and changed their natural kinematics by increasing the loading on their ACLR limb.

To our knowledge, our study is the first to examine the effect of sex on limb loading metrics during a bilateral bodyweight squat in patients recovering from ACLR. We observed that females offloaded their ACLR limb more and were more asymmetric during the bilateral squatting task compared with their male counterparts. Our results align with those of related studies whose authors investigated the

Table 3. Descriptive Statistics for Limb Loading Metrics and PROs

Measure	Mean ± SD
Limb loading metrics	
Normalized peak force, ACLR limb, N/kg	6.62 ± 1.56
UCL, ACLR limb, %	48.83 ± 9.28
Normalized peak force, contralateral limb, N/kg	7.33 ± 1.61
UCL, contralateral limb, %	51.17 ± 9.28
Peak force LSI, absolute value, %	24.69 ± 18.79
PROs	
IKDC	73.51 ± 13.55
KOOS Symptom	82.27 ± 13.40
KOOS Pain	88.68 ± 11.36
KOOS ADLs	95.78 ± 6.62
KOOS Sport	72.90 ± 21.16
KOOS QOL	60.64 ± 19.51
ACL-RSI	57.89 ± 23.78
TAS Preinjury	7.79 ± 1.89
TAS Current	4.69 ± 1.50

Abbreviations: ACLR, anterior cruciate ligament reconstruction; ACL-RSI, Anterior Cruciate Ligament Return to Sport After Injury; ADLs, activities of daily living; IKDC, International Knee Documentation Committee Subjective Knee Form; KOOS, Knee Injury and Osteoarthritis Score; LSI, limb symmetry index; PROs, patient-reported outcomes; QOL, quality of life; TAS, Tegner Activity Scale; UCL, unilateral cumulative load.

Table 4. Spearman ρ Correlation Coefficient Values for Limb Loading Metrics and PROs Across ACLR and Contralateral Limbs

Limb Loading Metrics	PROs								
	IKDC	KOOS Symptom	KOOS Pain	KOOS ADLs	KOOS Sport	KOOS QOL	ACL-RSI	TAS Preinjury	TAS Current
Normalized peak force, ACLR limb, N/kg	0.10	0.03	−0.02	0.11	0.03	0.22	0.03	0.11	**0.18[a]**
UCL, ACLR limb, %	0.11	0.17[a]	0.03	0.19[a]	−0.10	0.07	0.08	0.15	0.09
Normalized peak force, contralateral limb, N/kg	−0.16	−0.23[b]	−0.07	−0.17[a]	−0.13	−0.13	−0.18[a]	−0.07	0.02
UCL, contralateral limb, %	−0.11	−0.17[a]	−0.03	−0.19[a]	−0.10	−0.07	−0.08	−0.15	−0.09
Peak force LSI, absolute value, %	−0.003	−0.06	0.08	−0.04	−0.01	0.01	−0.01	−0.04	−0.04

Abbreviations: ACLR, anterior cruciate ligament reconstruction; ACL-RSI, Anterior Cruciate Ligament Return To Sport After Injury; ADLs, activities of daily living; IKDC, International Knee Documentation Committee Subjective Knee Form; KOOS, Knee Injury and Osteoarthritis Score; LSI, limb symmetry index; PROs, patient-reported outcomes; QOL, quality of life; TAS, Tegner Activity Scale; UCL, unilateral cumulative load.

[a] $P < .05$.

[b] $P < .01$.

influence of biological sex on 3D kinematic and kinetic variables during a variety of tasks such as walking and jump landings.[15–17] Results of these studies, evaluating explosive tasks, suggested that females had worse movement quality and decreased muscle activity compared with their male counterparts after ACLR.[15,16] However, during a mild walking task the opposite conclusion was made. Males with a noncontact mechanism of injury were found to offload their ACLR limb more than their female counterparts and males who sustained a contact mechanism of injury.[39] The difference between the explosive tasks and walking indicates that an intermediary task such as a bilateral squatting task could be an appropriate area of intervention. Whereas a squat is not as physically demanding as a jump-landing explosive task, it can be more demanding than leisure walking when progressed appropriately. Given the nature of a bilateral squatting task, it could have utility in highlighting loading asymmetries between sexes. Additionally, it is possible that females after ACLR cope differently in their biomechanical movement patterns compared with their male counterparts. In our study, the presence of sex differences for limb loading metrics at approximately 5 months post-ACLR indicates that clinicians may intervene during structured ACLR rehabilitation. The impact of the observed sex differences in limb loading on postoperative rehabilitation, RTA decision-making, and reinjury risk is an area of future research.

Weak relationships found between limb loading metrics and PROs demonstrate that as a patient becomes more symmetric their subjective knee function improves. One significant relationship was observed for the normalized peak force variable: for patients who applied less force on the contralateral limb, their KOOS Symptom score improved. This finding is similar to those of previous researchers who found that individuals after ACLR who were considered symptomatic via KOOS scores offloaded their ACLR limb compared with their contralateral limb during a walking task.[25,27] We also observed that as the contralateral limb UCL decreased and the ACLR limb UCL increased, KOOS Symptom and ADLs subscale scores improved. The KOOS ADLs subscale questions address the degrees of difficulty when performing everyday tasks (eg, rising from sitting, getting in or out of a car, getting on or off the toilet) that frequently mimic the motion of a bodyweight bilateral squat.[28] These relationships observed potentially indicate that regardless of limb, patients who load their limbs more unevenly have a lower perception of their ability to complete ADLs. A similar relationship was observed in which individuals who had greater normalized limb loading peak force from their ACLR limb were currently participating in higher levels of physical activity as determined by the TAS. The only relationship between any loading metric and the ACL-RSI was a negative relationship between the ACL-RSI score and the normalized peak force from the contralateral limb. This is somewhat contradictory to the finding of a previous study in which no relationship was observed between limb loading during walking and kinesiophobia as determined by the Tampa Scale for Kinesiophobia.[40] This is likely due to the difference in limb loading requirements during gait compared with a squatting task. Ceiling effects for the KOOS Pain, KOOS ADLs, KOOS Sport, and TAS preinjury were observed and should be taken into consideration.

A bilateral bodyweight squat is a commonly used exercise during rehabilitation sessions and when performing ADLs. The ability to measure limb loading objectively and precisely during a commonly performed movement (ie, bilateral squat) gives clinicians tools to practice personalized medicine. All PRO measures used in the current study are freely available online for clinical use. The implementation of PRO measures could give clinicians insight as to their patients' readiness to RTA but also could be used as an indicator of the potential adoption of asymmetric limb loading movement patterns that may need intervention. Personalizing a patient's rehabilitation protocol to fit their individualized needs using a translatable clinical measure allows for more targeted interventions and ultimately better outcomes. During traditional RTA testing batteries, clinicians commonly use strength measures, functional tasks, and subjective functional PROs.[1] Few researchers have incorporated a squatting task variation in an RTA protocol, and few have used a bilateral bodyweight squat in their arsenal of tests.[1,41] Researchers have suggested that the optimal time for individuals to RTA can be anywhere between 9 and 12 months after surgery.[1,41] The average time after ACLR for the individuals in our study was approximately 5 months, indicating that patients may need to be reexamined closer to the time of their clearance to RTA. It is currently unclear whether these loading asymmetries persist past 5 months after ACLR. The evidence provided in our study highlights the need to further investigate the influence of limb loading metrics after ACLR during serial assessment and explore the feasibility of implementing a squatting task into an RTA protocol.

Limitations

Participants in this study underwent rehabilitation with their preferred clinician; therefore, we did not control for postoperative rehabilitation. Additionally, rehabilitation plans were not recorded, nor was compliance in completing their recommended protocol, although all patients were given the same postoperative general protocol by their surgeons. Our study required 1 visit to the laboratory at a time point when rehabilitation may not have been complete; therefore, the findings of this study should be considered an interim functional analysis as patients are recovering from ACLR. Given the cross-sectional study design, it is possible that patients had differences in their limb loading symmetries before injury. A single testing session may not be representative of overall patient function after ACLR; the importance of repeat testing to track progress, evaluating the efficacy of exercise interventions, and making informed health care decisions is immeasurable.

Throughout the testing session we standardized squat pace using a metronome, which could have influenced preferred squatting pace and may be less generalizable to functional scenarios during activity or sport. However, it has been observed that there is a moderate to strong relationship between the biomechanical movement profiles during a bilateral squatting task and a drop-landing task in individuals after ACLR.[8] This relationship suggests that movement patterns during a squatting task could carry over during a high-demand dynamic jump-landing task, indicating that a squatting task could be a useful proxy to evaluate the quality of movement patterns in a safe manner. Additionally, a limitation of this study was a lack of kinematic data collection. The integration of motion-capture capabilities would elucidate during which phase of the squatting trial patients are offloading their ACLR limb more than their contralateral limb. Future researchers should consider implementing kinematic data collection when investigating limb loading characteristics during a bilateral squatting task.

CONCLUSIONS

Approximately 5 months postsurgery, patients recovering from ACLR were observed offloading their ACLR limb to their contralateral limb. Females offloaded their ACLR limb more than males. From these findings, clinicians may consider confirming that their patients, particularly their female patients, are not offloading their ACLR limb during functional tasks, such as a squat. This would help facilitate good biomechanics and minimize the adoption of poor movement patterns that may increase reinjury risks. Additionally, the relationship, albeit small, between limb loading metrics and PROs suggests that individuals who are asymmetrically loading their limbs during a bodyweight bilateral squatting task perceive a decreased ability to perform their ADLs. The evidence provided in our study highlights the need to further investigate the influence of limb loading metrics after ACLR and explore the feasibility of implementing a bilateral squatting task into an RTA protocol.

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