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original research

Drop-Landing Performance and Knee-Extension Strength After Anterior Cruciate Ligament Reconstruction

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Context: Individuals with a history of anterior cruciate ligament reconstruction (ACLR) are at greater risk of reinjury and developing early-onset osteoarthritis due to persistent abnormal joint loading. Real-time clinical assessment tools may help identify patients experiencing abnormal movement patterns after ACLR.

Objective: To compare performance on the Landing Error Scoring System (LESS) between participants with ACLR and uninjured control participants and to determine the relationship between LESS score and knee-extension strength in these participants.

Design: Controlled laboratory study.

Setting: Research laboratory.

Patients or Other Participants: Forty-six recreationally active participants, consisting of 22 with ACLR (12 men, 10 women; age = 22.5 ± 5.0 years, height = 172.8 ± 7.2 cm, mass = 74.2 ± 15.6 kg, body mass index = 24.6 ± 4.0) and 24 healthy control participants (12 men, 12 women; age = 21.7 ± 3.6 years, height = 168.0 ± 8.8 cm, mass = 69.2 ± 13.6 kg, body mass index = 24.3 ± 3.2) were enrolled.

Main Outcome Measure(s): Bilateral normalized knee-extension maximal voluntary isometric contraction (MVIC) torque (Nm/kg) and LESS scores were measured during a single testing session. We compared LESS scores between groups using a Mann-Whitney *U* test and the relationships between LESS scores and normalized knee-extension MVIC torque using Spearman ρ bivariate correlations.

Results: The ACLR participants had a greater number of LESS errors (6.0 ± 3.6) than healthy control participants (2.8 ± 2.2; t_{44} = –3.73, *P* = .002). In ACLR participants, lower normalized knee-extension MVIC torque in the injured limb (ρ = –0.455, *P* = .03) was associated with a greater number of landing errors.

Conclusions: Participants with ACLR displayed more errors while landing. The occurrence of landing errors was negatively correlated with knee-extension strength, suggesting that weaker participants had more landing errors. Persistent quadriceps weakness commonly associated with ACLR may be related to a reduced quality of lower extremity movement during dynamic tasks.

Key Words: quadriceps weakness, Landing Error Scoring System, knee-extension torque

Key Points

- Participants with anterior cruciate ligament reconstruction had more landing errors than healthy control participants.
- Landing errors were negatively correlated with knee-extension strength, suggesting that weaker participants demonstrated more landing errors.
- Persistent quadriceps weakness, which is associated with anterior cruciate ligament reconstruction, may be related to poorer-quality lower extremity movement during dynamic tasks.

Anterior cruciate ligament (ACL) injuries are common in the athletic population, and ACL reconstruction (ACLR) is the most common intervention to restore joint stability.[1] However, despite successful surgical intervention, ACL injury may result in persistent lower extremity weakness and negative long-term effects on joint health.[2] Currently, active individuals are permitted to return to sport based on a variable set of criteria established by clinicians and supported by research; yet in many cases, these criteria do not include quantifiable analyses of movement patterns that measure persistent alterations in knee-joint loading and prospectively monitor the potential risk for knee injury.[3–5] When making decisions regarding return to activity and rehabilitation strategies, clinicians must have access to easy, time-efficient tools that produce objective clinical findings to better assess individuals with a history of injury.

Individuals with ACLR experience neuromuscular and sensorimotor deficits that can persist long after completion of rehabilitation.[2,6] These deficits result in reduced physical activity level, patient-reported knee function, and quadriceps strength and activation and alterations in functional performance[7–11] that may have major implications for knee-joint reinjury[7,12] and the development of posttraumatic osteoarthritis (OA).[13–15] Assessing landing biomechanics after ACLR provides a clinically relevant method to evaluate global lower extremity function, including muscle strength and postural control during a common functional movement pattern. In addition, alterations in frontal-plane and sagittal-plane

Table 1. Descriptive Group Statistics (Mean ± SD)

Characteristic	Group: Healthy Control	Group: Anterior Cruciate Ligament Reconstruction	*P* Value	t_{44} Value
Sex			.97	NA
Men	12	12		
Women	12	10		
Age, y	21.7 ± 3.6	22.5 ± 5.0	.58	−0.59
Height, cm	168.0 ± 8.8	172.8 ± 7.2	.05[a]	−2.05
Mass, kg	69.2 ± 13.6	74.2 ± 15.6	.27	−1.13
Body mass index	24.3 ± 3.2	24.6 ± 4.0	.81	−0.24
Pain in last 24 h, cm	0.0 ± 0.0	0.0 ± 0.1	.33	−0.97
Pain during 10 squats, cm	0.1 ± 0.4	0.4 ± 0.6	.12	−1.61
Tegner Activity Level Scale score (range, 0–10)	6.3 ± 1.2	6.4 ± 1.2	.53	−0.63
Lower Extremity Functional Scale score (range, 0–80)	79.5 ± 2.1	74.8 ± 7.2	.004[a]	3.07
2000 International Knee Documentation Committee Subjective Knee Evaluation Form score (range, 0–100)	99.3 ± 6.7	87.2 ± 12.6	<.001[a]	4.69
Time since surgery, mo	NA	31.5 ± 23.5	NA	NA
Graft source	NA	12 hamstrings autograft, 10 bone-patellar tendon-bone	NA	NA

Abbreviation: NA, not applicable.

[a] Indicates between-groups difference ($P \leq .05$).

biomechanics have been hypothesized to predict which individuals may be at risk for reinjury or long-term joint degeneration due to persistent aberrant joint loading.[16] Most studies have focused on jump landings in the healthy population to understand the risk factors for initial ACL injury, but the neuromuscular and motor-control demands present during jump-landing tasks also provide a useful tool for assessing recovery and post-ACLR injury risk.[17] During double-limb landings after ACLR, individuals have consistently shown reductions in external knee-flexion moment and hip-extension moment, whereas external ankle plantar-flexion moments increased immediately after initial contact compared with the contralateral limb and with healthy matched control participants.[16–18] These findings suggest a tendency toward quadriceps avoidance coupled with compensatory adaptations at the hip and ankle. Unfortunately, whereas these compensations may enable completion of the task and potentially a higher level of daily activity, they also represent a substantial deviation from normal movement patterns, which may help to explain why individuals with ACLR are at greater risk for reinjury,[19] contralateral knee injury,[19,20] and development of premature knee-joint OA.[21]

Understanding the persistent functional compensation patterns that can be assessed clinically after ACLR is essential for targeting patient-specific treatments and identifying which patients may be at greater risk for subsequent injury. The Landing Error Scoring System (LESS) is a viable clinical tool designed to predict lower extremity injury risk by identifying high-risk movement patterns during a drop-landing task.[22] The LESS has mainly been used as a measure of primary knee-injury risk and only recently has been investigated in a predominantly female sample of individuals with ACLR who committed a greater number of errors than healthy matched control participants.[23] In addition, the relation of the LESS to common patient-reported outcome measures and modifiable clinical measurements has not been described in this population. Therefore, the primary purpose of our study was to compare performance on the LESS between participants with ACLR and healthy control participants. We hypothesized that participants with ACLR would have greater LESS scores (ie, more landing errors) than healthy control participants. Our secondary purpose was to quantify the relationship between the LESS score and knee-extension strength, as well as self-reported measures of physical activity, pain, and lower extremity function in participants with ACLR and in healthy participants. We hypothesized that greater LESS scores would be negatively related to deficits in knee-extension strength, physical activity level, and lower extremity function in participants with ACLR.

METHODS

This investigation was a descriptive laboratory study, and all measures were completed during a single testing session.

Participants

Twenty-two participants with ACLR and 24 healthy control participants enrolled in this study (Table 1). Individuals were assigned to the control group if they had no history of substantial lower extremity injury and no lower extremity injury within the 6 weeks before the study. Volunteers with ACLR were included if they had a history of primary, unilateral, uncomplicated ACLR with no substantial chondral resurfacing at least 9 months before enrolling. In addition, all ACLR participants had returned to recreational activity after clearance from a physician. All participants provided written informed consent, and the study was approved by the Institutional Review Board for Health Sciences Research at the University of Virginia.

Procedures

After enrollment, participants completed patient-reported outcome measures, including the 2000 International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form,[24] Lower Extremity Functional Scale,[25] Tegner Activity Level Scale,[26] and a visual analog scale for knee pain during the previous 24 hours and after performing 10 consecutive body-weight–resisted squats with their hands on their hips. Next, they completed bilateral normalized knee-

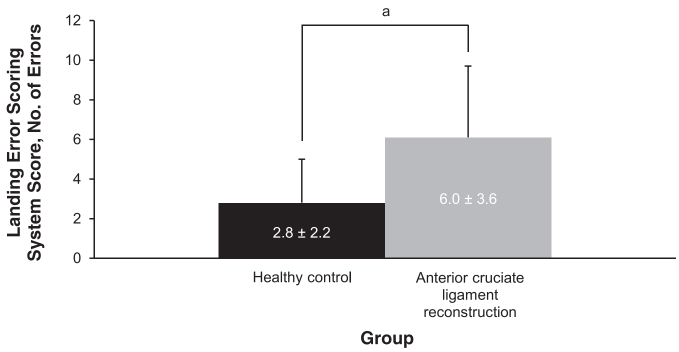

Figure 1. Comparison of landing errors between healthy control participants and participants with anterior cruciate ligament reconstruction. [a] Indicates a difference between groups ($P = .002$).

extension maximal voluntary isometric contraction (MVIC) testing followed by the LESS.

Normalized Knee-Extension MVIC Torque. Participants were secured in a Biodex multimode dynamometer (System 3; Biodex Medical Systems Inc, Shirley, NY) with the hips and knees at 90° of flexion. Data were digitized at 125 Hz (model MP150; BIOPAC Systems Inc, Santa Barbara, CA). To expedite the testing procedure, the left limb was tested first for all participants, regardless of history of injury. Participants were secured to the Biodex dynamometer using a waist strap, and the testing limb was secured to the dynamometer arm 2 cm above the calcaneus. Next, they familiarized themselves with the equipment and the isometric knee-extension task, during which they were instructed to contract once at 25%, 50%, and 75% and twice at 100% of perceived maximum ability. Participants rested for at least 1 minute before data collection. During all knee-extension MVIC contractions, we provided constant oral encouragement, such as "keep going" and "push harder," until a torque plateau was maintained for at least 2 seconds, and we instructed participants to maintain good seated posture.[27] Trials in which participants did not achieve a stable torque plateau or maintain good testing posture were discarded, and replacement trials were completed. Participants rested at least 1 minute between test contractions to prevent fatigue. After completion, the same procedures were conducted on the contralateral limb. Knee-extension MVIC torque was normalized to body mass (×Nm/kg) to allow for comparison among participants.

Landing Error Scoring System. Drop-landing procedures were consistent with the original description of the LESS.[22] Participants jumped from a 30-cm-tall box onto a target located 50% of their own heights away from the box. They were instructed to jump out horizontally to the landing zone and, immediately after landing, to attempt a maximum vertical jump. Two standard handheld camcorders (HF R400 HD Flash Camcorder; Canon USA, Inc, Melville, NY) captured the drop-landing task for evaluation at a later time using the LESS. Both cameras were 48 in (121.92 cm) from the ground and secured to free-standing tripods, with 1 camera 136 in (345.44 cm) lateral to the landing zone and the other camera 136 in (345.44 cm) anterior to the landing zone. Before we recorded trials, participants practiced until they were comfortable with the task. They rested 30 seconds between trials. A mean score from 3 jump landings was used to calculate the LESS score for each participant.[22] We assessed the involved limb for the ACLR group and the self-identified nondominant limb for the control group.

Statistical Analysis

Means and standard deviations were calculated for all demographic and outcome variables. We used independent-samples t tests to determine group differences in demographics, excluding sex (for which a Fisher exact test was used), and a Mann-Whitney U test to compare LESS scores between groups. Paired-samples t tests were performed to assess the between-limbs differences in normalized knee-extension MVIC torque within each group. Cohen d effect sizes and associated 95% confidence intervals were also calculated for the between-groups differences in LESS scores. Spearman ρ correlations were used to quantify the relationship between LESS score and both bilateral normalized knee-extension MVIC torque and participant-reported outcome measures. We chose Spearman ρ correlations because LESS scores are not truly continuous variables, so a nonparametric correlation was the more conservative approach. The α level was set at $\leq .05$. Statistical analysis was performed using SPSS statistical software (version 20.0; IBM Corporation, Armonk, NY).

RESULTS

Participants with ACLR exhibited greater LESS scores than healthy control participants (Cohen $d = 1.45$, 95% confidence interval = 0.80, 2.10; Figure 1). They also exhibited a between-limbs difference for normalized knee-extension MVIC torque (involved = 2.50 ± 0.84 Nm/kg, uninvolved = 2.92 ± 0.65 Nm/kg; $t_{21} = 3.49$, $P = .002$), whereas healthy control participants did not exhibit a between-limbs difference (dominant = 2.90 ± 0.59 Nm/kg, nondominant = 2.77 ± 0.50 Nm/kg; $t_{23} = 1.52$, $P = .14$). For all participants, more landing errors were moderately related to lower IKDC scores (Table

Table 2. Spearman ρ Correlations Within Groups Between Landing Error Scoring System Score and Participant-Reported Descriptive Information

Variable	Group: Healthy Control	Anterior Cruciate Ligament Reconstruction	Combined
Pain in last 24 h, cm	0.12	−0.16	−0.07
Pain during 10 squats, cm	0.04	0.25	0.27
Tegner Activity Level Scale score (range, 0–10)	−0.11	−0.44[a]	−0.24
Lower Extremity Functional Scale score (range, 0–80)	0.10	−0.24	−0.26
2000 International Knee Documentation Committee Subjective Knee Evaluation Form score (range, 0–100)	−0.28	−0.11	−0.39[a]
Time since surgery, mo	NA	−0.27	NA

Abbreviation: NA, not applicable.

[a] Indicates correlation ($P \leq .05$).

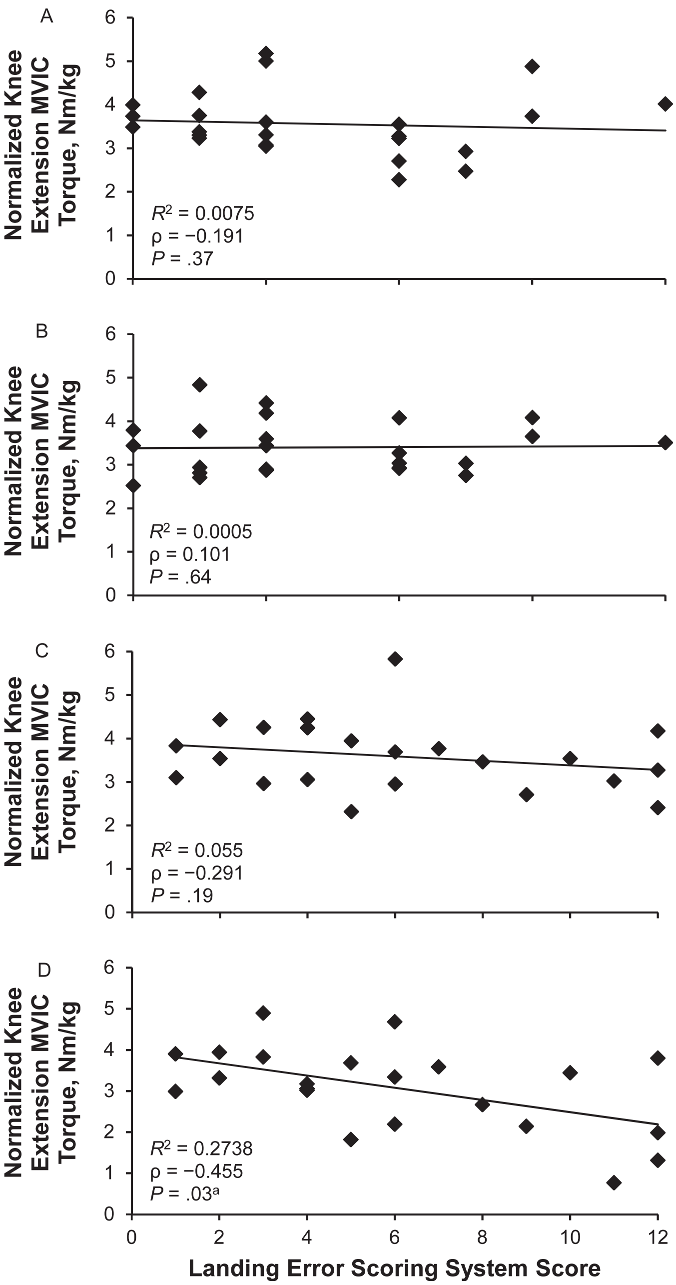

Figure 2. Spearman ρ correlations between normalized knee-extension maximal voluntary isometric contraction (MVIC) torque and Landing Error Scoring System score in control participants for the A, dominant and B, nondominant limbs and for participants with anterior cruciate ligament reconstruction for the C, uninvolved and D, involved limbs. [a] Indicates a correlation ($P < .05$).

2). For participants with ACLR, more landing errors were moderately related to lower current Tegner scores (Table 2) and lower involved-limb normalized knee-extension MVIC torque (Figure 2). Landing errors by LESS item for each group are shown in Figures 3 and 4.

DISCUSSION

Easy, time-effective assessment tools that can be used clinically with little equipment are invaluable when attempting to monitor a patient's progress throughout rehabilitation and develop a plan for return to physical activity after ACLR. We used the LESS to investigate the effect of ACLR on the quality of lower extremity biomechanics while landing. We confirmed our hypothesis that participants with ACLR would have higher LESS scores, indicating more landing errors. The ACLR participants committed an average of 6.0 ± 3.6 errors, which is consistent with the findings of a previous study[23] involving participants with a similar activity level and time since surgery. In addition, we found that higher LESS scores were related to quadriceps weakness and a lower physical activity level in participants with ACLR. These observations suggested that after ACLR, individuals may experience altered movement patterns that persist beyond rehabilitation and return to physical activity. Monitoring landing biomechanics may help provide quantifiable milestones for rehabilitation that can aid in making return-to-activity decisions.

Paterno et al[19] reported that individuals with ACLR were at nearly 6 times greater risk of subsequent ACL injury to the previously injured knee or the contralateral limb than healthy individuals at a 2-year follow up. In addition, these individuals are thought to be at greater risk of early-onset tibiofemoral and patellofemoral joint OA.[21] Currently, clinicians use a wide variety of quantitative and nonquantitative assessment tools throughout rehabilitation to monitor patient progress and readiness to return to activity; however, injury rates continue to rise.[28] The LESS has been used widely as a prospective indicator of knee-injury risk in healthy control individuals; however, altered lower extremity biomechanics have consistently been reported during functional tasks at various follow-up points after ACLR.[17,29,30] In healthy individuals, a LESS score greater than 6 has been related to greater injury risk, but a similar threshold has not been established in individuals with injury histories.[22] When applying the threshold value of a LESS score greater than 6.0 to our sample, we determined that 10 of 22 participants with ACLR exhibited potentially harmful lower extremity movement patterns, whereas only 4 of 24 control participants scored greater than 6.0. Further investigation may be warranted to test the hypothesis of whether the LESS score can predict subsequent injury, such as graft failure, patellofemoral pain, or joint degeneration, in people with ACLR.

When looking at which errors were committed most commonly in each group, control participants most often landed with reduced knee flexion (20.8%) and increased knee valgus (20.8%) at initial contact, coupled with increased knee-valgus displacement (33.3%) and trunk-flexion displacement (25.0%; Figure 3). These errors are consistent with previously reported risk factors for primary ACL injury; however, the low overall LESS scores reported in this group indicated a potentially low risk of knee injury.[22] Participants with ACLR commonly exhibited reduced knee (72.7%) and hip (45.5%) flexion and increased knee valgus (40.9%), forward trunk flexion (54.5%), and lateral trunk flexion (40.9%) at initial contact (Figure 4). In addition, participants with ACLR had a high likelihood of increased knee-valgus displacement (54.5%) throughout landing. Increases in knee-valgus displacement[31] and lateral trunk flexion[32] have been linked to increased loading of the ACL, whereas decreases in knee flexion and hip flexion at the point of initial contact have been linked to increased overall knee-joint loading during functional activities.[11,30] The combination of these risk

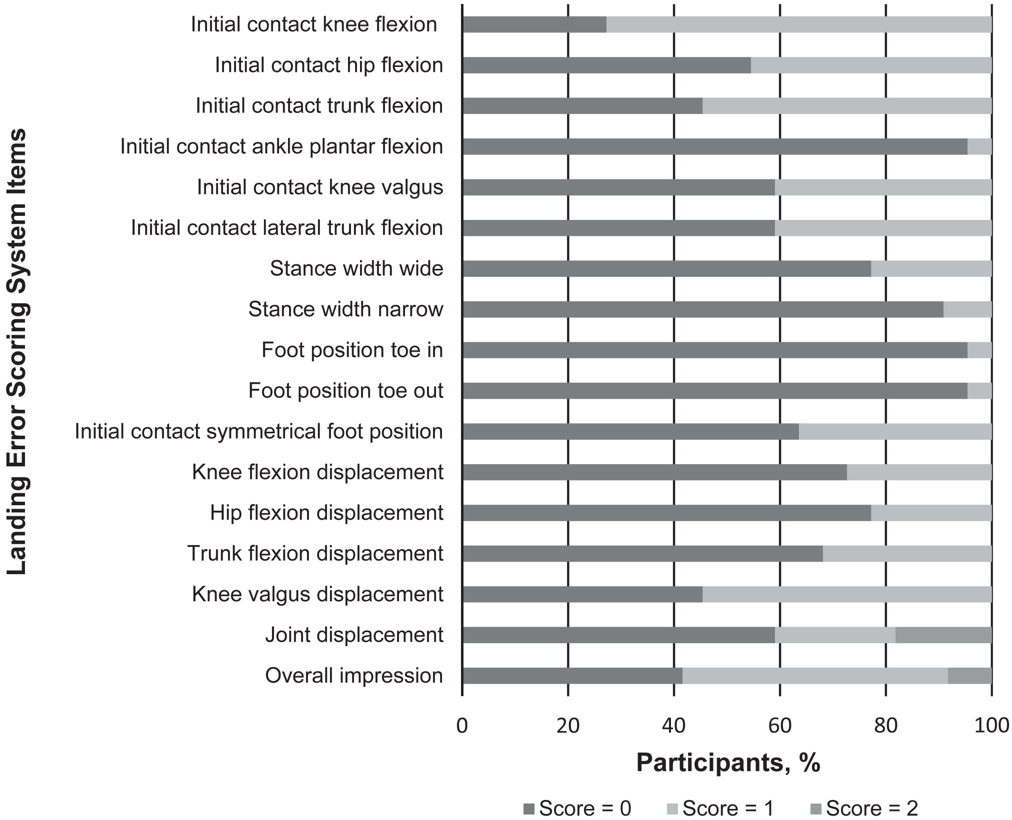

Figure 3. Percentage breakdown of scores on the individual items of the Landing Error Scoring System for healthy control participants.

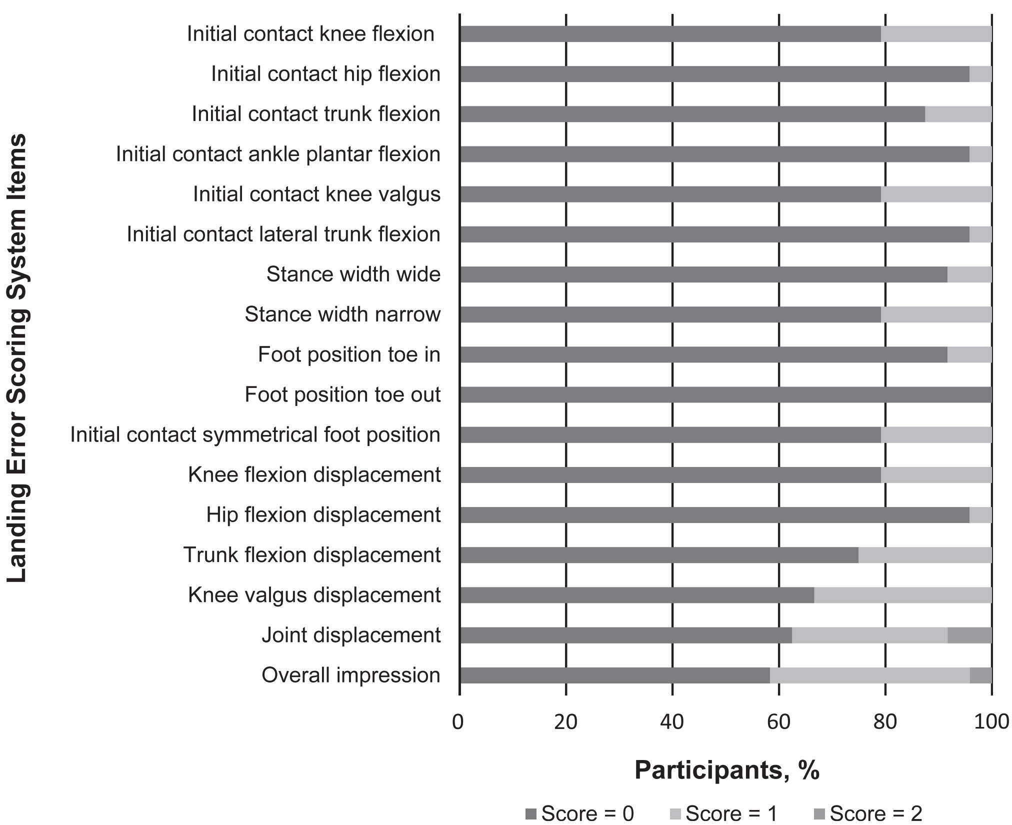

Figure 4. Percentage breakdown of scores on the individual items of the Landing Error Scoring System for participants with anterior cruciate ligament reconstruction.

factors for acute and potential long-term knee-joint injury highlights the detrimental effect of returning to physical activity if optimal neuromuscular control and lower extremity movement patterns are not restored after ACLR.

Evidence supports the hypothesis that lower extremity biomechanics change after ACLR. For example, researchers[17,29,30] have reported that external knee-flexion moment and peak knee-flexion angle during the loading phase of jump landings were less for participants with ACLR than for healthy control participants, suggesting an alteration in landing technique and force attenuation. These observations reflect a more knee-extended landing position with a smaller contribution of the knee extensors to combat the forces imposed on the knee joint during this high-loading task. Similar to other researchers who have used more sophisticated motion-analysis techniques, we found that the asymmetrical quadriceps strength driven by persistent reductions in strength in the involved limb is related to alterations in lower extremity movement patterns.[30,33] In this case, individuals experiencing weakness of the involved limb after ACLR were more likely to have higher LESS scores, indicating potentially harmful movement patterns associated with knee-injury risk (Figure 2). The return of normal bilateral quadriceps strength after ACLR represents an important and often frustrating clinical rehabilitation goal. Persistent reductions in quadriceps strength are thought to have major negative implications for knee-joint health after injury due to the inability to dynamically absorb forces at the joint during functional movement.[34] The observation that quadriceps strength of the involved limb within the ACLR group was related to LESS score (accounting for 27.4% of the variance in LESS score) provides further evidence that quadriceps weakness has implications for normal movement patterns while highlighting simple intervention strategies that may reduce subsequent injury risk.

Compared with uninjured individuals, patients commonly have reduced knee function[35] and physical activity levels[7,36] after ACLR. These changes in patient-reported function may persist for several years after the initial procedure despite the patient's receiving clearance to return to activity. In addition, researchers[37–39] have shown a strong relationship among persistent quadriceps dysfunction, functional performance, and self-reported knee function in patients with ACLR. In our investigation, participants with ACLR reported activity levels similar to those of the control group (Table 1); however, within the ACLR group, those reporting lower physical activity levels were more likely to exhibit potentially harmful landing biomechanics (Table 2). In addition, a relationship was not present in the ACLR group alone, but when all participants were considered together, those with lower self-reported knee function also had potentially harmful landing biomechanics. These findings, combined with observations by other researchers, represent an interesting and potentially clinically valuable interaction among poor patient-reported function, quadriceps dysfunction, and functional performance that reinforces the importance of a multifactorial approach to functional assessment before return to activity after ACLR.

Our study had several limitations that should be considered when interpreting the results. These data were part of a larger cross-sectional investigation. Given the limitations in this type of study design, we were not able to achieve as much experimental control as a prospective design would have allowed. We recruited a relatively homogeneous sample of patients based on demographics and physical activity level; however; the participants with ACLR had diverse experiences with rehabilitation after surgery and a wide range of times since surgery (31.5 $\pm$ 23.5 months). In addition, we were limited to assessment of isometric knee-extension strength at 90° of knee flexion. Despite the relationship between involved limb strength and LESS score in the ACLR group, future investigations should focus on more dynamic modes of strength assessment that are not limited to dynamometers.

CONCLUSIONS

Participants with ACLR displayed more errors while landing. Landing errors were negatively correlated with knee-extension strength, suggesting that weaker participants had more landing errors. Persistent quadriceps weakness commonly associated with ACLR may be related to poorer-quality lower extremity movement during dynamic tasks.

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