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Jump-Landing Mechanics After Anterior Cruciate Ligament Reconstruction: A Landing Error Scoring System Study

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Context: The Landing Error Scoring System (LESS) is a clinical evaluation of jump-landing mechanics and may provide useful information in assisting with return-to-sport decisions in patients after anterior cruciate ligament reconstruction (ACLR). However, it is currently unknown how patients with ACLR perform on the LESS compared with healthy controls.

Objective: To determine if the total LESS score differed between individuals with ACLR and healthy controls and to determine the types of errors that differ between groups.

Design: Cross-sectional study.

Setting: Research laboratory.

Patients or Other Participants: A total of 27 individuals with unilateral ACLR (age = 19.8 ± 1.8 years, height = 170 ± 5.5 cm, mass = 68.8 ± 11.9 kg) and 27 controls (age = 20.5 ± 1.7 years, height = 169 ± 8.4 cm, mass = 66.6 ± 9.0 kg) with no history of ACLR.

Intervention(s): Each participant completed 3 trials of a standardized jump-landing task.

Main Outcome Measure(s): Each jump landing was assessed for specific postures using standardized LESS criteria by a blinded evaluator. Individual LESS items were summed to create a total LESS score. The dominant limb was assessed in the control group, and the reconstructed limb was assessed in the ACLR group.

Results: The ACLR group had higher LESS scores compared with controls (ACLR: 6.7 ± 2.1 errors, control: 5.6 ± 1.5 errors, $P = .04$). Additionally, the ACLR group was more likely to err when landing with lateral trunk flexion (Fisher exact test, $P = .002$).

Conclusions: Individuals with ACLR had worse landing mechanics as measured by the LESS. Lateral trunk deviation may be related to quadriceps avoidance in the reconstructed limb or poor trunk neuromuscular control. The LESS is useful for evaluating landing errors in patients with ACLR and may help to identify areas of focus during rehabilitation and before return to sport.

Key Words: musculoskeletal injuries, jump landing, trunk, core neuromuscular control

Key Points

- Individuals with anterior cruciate ligament reconstruction had higher Landing Error Scoring System scores (ie, worse landing mechanics) than the control group.
- Errors in the Landing Error Scoring System were most common for lateral trunk flexion away from the reconstructed limb in patients after anterior cruciate ligament reconstruction.

Second anterior cruciate ligament (ACL) injury rates range from 12% to 26% and include injury to both the ipsilateral (graft failure or retear) and contralateral ACL.[1–3] When compared with the general population, rates for these injuries are highest in individuals who return to sport and participate in high-risk activities.[1–3] In fact, individuals with prior ACL injury and reconstruction are 15 times more likely to suffer a second ACL injury than those with no history of ACL rupture.[3] Paterno et al[4] illustrated this point by tracking individuals with ACL reconstruction (ACLR) for 1 year after return to sport. Thirteen of 56 athletes (23%) who returned to cutting and pivoting sports suffered a second ACL injury (10 contralateral, 3 ipsilateral). This elucidates the difficulty in safely returning patients to activity, as all had completed a rehabilitation program and were cleared by their health care providers to return to sport. Most return-to-activity guidelines are based on time from surgery, stability of the graft, and functional ability rather than biomechanical movement patterns that have been shown to increase an individual's risk for ACL injury.[4–6]

Lower extremity kinematics and kinetics differ between individuals with ACLR and healthy controls when examined using 3-dimensional motion analysis.[7–9] Delahunt et al[8] compared kinematics during a drop vertical jump in 14 females with ACLR (average of 4.4 years after surgical reconstruction) with healthy controls. The reconstructed group had greater peak hip- and knee-adduction angles, greater hip internal-rotation angles, and decreased peak knee-flexion angles.[8] Additionally, female soccer players with ACLR have been reported to exhibit greater knee-abduction angles and adductor moment during a side-step cutting maneuver than healthy controls.[7] Furthermore, patients with reconstructions landed with greater force on the healthy limb compared with the reconstructed limb.[10] Together, these studies establish that individuals with ACLR have movement strategies that may be partially responsible for high second-injury rates in this population.

The purpose of rehabilitation after ACLR depends on the goals of each patient. In adolescents, in whom ACLR is common, patients often have the goal of returning to sport. Current guidelines dictate that a patient's reconstructed extremity be greater than 90% of the reference limb during clinical testing. These tests often encompass a variety of factors associated with performance, such as quadriceps and hamstrings strength and hop tests. Oftentimes, performance on these tests is based on a single factor, such as the time to completion or distance travelled. Although these metrics are important, how an individual moves during these activities should also be examined. Evaluating the quality of motion may provide clinicians with useful information about neuromuscular control during high-risk activities that can be addressed during the rehabilitation process and can also be part of the return-to-sport decision criteria.

One of the most researched tools available to evaluate quality of motion during landing is the Landing Error Scoring System (LESS). The LESS evaluates 17 items or errors related to landing position that are associated with ACL loading.[11] Errors are summed, with a higher score theoretically associated with a higher risk of injury. The LESS has good to excellent interrater and intrarater reliability and has been validated against 3-dimensional motion analysis.[11,12] Females have worse (higher) LESS scores than males,[11,13] and the types of errors differ between sexes. Females are more likely to have poor landing technique, with less hip and knee flexion at initial contact, increased knee valgus with a wide stance, and decreased knee-flexion displacement.[13] Males are more likely to commit errors during landing due to toeing out, landing heels first, and landing with an asymmetrical foot position.[13] The LESS score can be improved using prepractice injury-prevention programs.[14] Previous researchers have focused only on healthy individuals with no history of injury, and given the elevated risk of injury in those with ACLR,[4] the LESS may be useful for evaluating movement mechanics and assisting with return-to-sport decision making. It is currently unknown if individuals with ACLR perform differently on the LESS or exhibit different errors on specific LESS items than healthy controls.

Therefore, the purpose of our investigation was to determine if total LESS scores differed between individuals with ACLR and healthy controls. A second purpose was to determine if the frequencies of errors for each LESS item differed between groups. We hypothesized that the ACLR group would have a higher total LESS score compared with healthy controls and that item-specific errors would be more frequently observed in the ACLR group.

METHODS

Participants

Twenty-seven individuals with unilateral ACLR and 27 healthy controls volunteered for this investigation. To qualify for the study, participants in the ACLR group met all of the following eligibility criteria: (1) sustained a unilateral ACL injury, (2) underwent surgical reconstruction, (3) completed rehabilitation, (4) were cleared by their physician to return to all levels of physical activity, (5) were 18 to 25 years of age, (6) sustained no lower extremity injury in the past 3 months, and (7) had no other history of lower extremity surgery. Control participants met criteria 5 through 7 and were matched by sex to the ACLR group. To determine the sample size, we used means and standard deviations from preliminary data as well as the previously published literature. A power analysis revealed that a minimum of 21 participants per group would be needed to detect a 1.5 error difference between groups ($\beta = 80\%$, $\alpha = .05$, standard deviation = 1.67 errors).[11]

Procedures

All testing was completed at the Wisconsin Injury in Sport Laboratory on the University of Wisconsin–Madison campus. All participants read and signed an informed consent document approved by the university's institutional review board before the study began. Height, mass, age, Tegner activity rating scale, and International Knee Documentation Committee (IKDC) 2000 knee function scores were recorded. The Tegner scale is one of the most common methods of assessing patient-administered activity level and is valid and reliable in patients with ACLR.[15] All testing was completed in the participant's personal athletic shoes and athletic attire. The jump-landing task has been previously described[11,14] and requires jumping from a 30-cm (12-in high) box set at a distance of 50% body height away from a landing area. Participants are instructed to jump a second time, immediately after the initial landing, for maximal height. Each participant performed 2 practice jumps, followed by 3 successful trials. A trial was considered *successful* if the individual jumped from the box using both feet, cleared the minimum distance, and performed the task in a fluid motion.[11] Participants were allowed to rest for 30 seconds between trials. Two standard 30-Hz video cameras (model HDC-SD80; Panasonic Corporation of North America, Newark, NJ) simultaneously recorded frontal and sagittal views of each person completing the jump landing.

To score the LESS, we advanced frontal and sagittal views frame by frame using QuickTime Player (version 7.7.4; Apple Inc, Cupertino, CA) to specific frames of interest. These frames included *initial foot contact with the ground* (which was defined as the first frame when the foot contacts the ground, the first frame when the entire foot was on the ground), and the frames of maximum knee flexion and maximum dynamic knee valgus.[11] Lower extremity and trunk position (LESS items 1–6) were graded at initial contact. Foot position was assessed at 3 time points: initial contact (item 11), when the entire foot was on the ground (items 7 and 8), and between initial contact and peak knee flexion (items 9 and 10).[11] Next, lower extremity and trunk motion were assessed again between initial contact and peak knee flexion or dynamic knee valgus (items 12–15). The final 2 items of the LESS (items 16 and 17) allow the rater to evaluate both the total amount of sagittal-plane displacement during the landing and the overall landing strategy. In ACLR participants, the reconstructed limb was evaluated, whereas in the control group, the dominant limb was evaluated. The *dominant limb* was defined as the limb

Table 1. Demographic Information for Each Group[a]

Characteristic	Group		P Value	t_{52}
	Control	Anterior Cruciate Ligament Reconstruction		
Sex (women, men)	23, 4	23, 4		
Height, cm	169.8 ± 8.8	169.6 ± 6.0	.77	−0.28
Mass, kg	66.2 ± 9.9	69.2 ± 12.9	.31	−0.98
Age, y	20.5 ± 1.6	19.9 ± 1.7	.18	1.43
Tegner activity level	5.7 ± 1.4	6.8 ± 1.7	<.01[b]	−2.71
International Knee Documentation Committee score	97.4 ± 5.7	83.8 ± 10.4	<.01[b]	5.83

[a] Values are means ± SDs.
[b] Statistically significant difference between groups.

used to kick a ball for maximal distance, which was standard procedure for grading the LESS in previous research.[11]

One examiner with more than 10 years of research experience scored all participants and all trials. A second investigator set up the front and side videos on a computer screen and covered the top portion of the videos with cardstock paper to obscure the identity of the participants. The order of the videos was randomized, and the primary examiner was blinded to group assignment. The videos were not of sufficient quality to identify scars. A reliability analysis was performed with the same procedures to determine if the evaluator was reliable in administering the LESS and to determine if it could be reliably administered in those with ACLR. To verify the intrarater reliability of the examiner, 20 participants (10 control and 10 with ACLRs) were randomly selected and graded a second time 2 weeks later to reduce recall by the primary grader. The evaluator was blinded to the previous LESS score, and the intrarater reliability was high (control: intraclass correlation coefficient $[ICC]_{2,1} = 0.85$, ACLR: $ICC_{2,1} = 0.90$).

Statistical Analysis

We used an analysis of covariance to examine differences in total LESS score between groups while controlling for activity level as measured by the Tegner scale. The Fisher exact test (FET) was calculated to determine differences between groups of the frequency of receiving an error on each specific LESS scoring item.[11] All statistical analyses were performed in IBM SPSS (version 20.0; IBM Corporation, Armonk, NY), and the level of significance for all statistical tests was set a priori at $P < .05$ except for the FET, which was adjusted to account for multiple comparisons at $P < .0029$ (0.05/17 LESS items).

RESULTS

Group demographics are found in Table 1. The average time from injury to testing was slightly more than 3 years (39.2 ± 17.6 months, range = 8–70 months, 25th percentile = 24 months, 50th percentile = 36 months, 75th percentile = 53 months), which is similar to the times in previously reported studies.[7,8] All ACL injuries were classified via self-report during the interview process as noncontact or indirect contact based on published classification recommendations.[16] Graft type in our patient population was representative of the most common grafts used for reconstruction, including bone-patellar tendon-bone (n = 15; 56%), semitendinosus-gracilis (n = 9; 33%), and allografts (n = 3; 11%). The most common mechanism of injury reported was cutting or pivoting (n = 19), followed by landing from a jump (n = 8).

We screened the data to ensure that assumptions were met for each statistical analysis. Baseline characteristics between groups were compared using independent-samples *t* tests (Table 1). Current activity level, as measured by the Tegner scale, was higher in the ACLR group, whereas IKDC score was higher in the control group. Because current activity level could theoretically influence movement patterns, it was used as a covariate in the analysis for the total LESS score. The ACLR group had a higher total LESS score than the control group (ACLR: 6.7 ± 2.1 errors; control: 5.6 ± 1.5 errors; $P = .04$, $F_{1,51} = 4.4$). For the frequency analysis, a participant was required to have scored an error in 2 of the 3 trials to have an error on any specific LESS item.[11] The frequency analysis showed that the ACLR group was more likely to receive an error for lateral trunk flexion (FET, $P = .002$) than the healthy controls. The observed frequencies within each group are shown in Table 2.

DISCUSSION

The primary objective of our study was to determine if the total LESS score was greater in individuals with a history of ACLR than in healthy uninjured controls. The total LESS score was greater in the ACLR group by an average of 1.1 errors (16% greater). Also, individuals with ACLR were more likely to receive errors for laterally flexing the trunk during landing. These findings support our hypotheses and also support the notion that individuals with ACLR have different landing strategies compared with healthy control participants.

Individuals with ACLR were more likely to receive an error for lateral trunk flexion during landing (LESS item 6) based on frequency observations using FET. A majority (63%) of ACLR individuals received this error, and post hoc analysis revealed that the trunk was shifted toward the contralateral limb in 15 of 17 cases. Lateral trunk flexion was identified as an error in only 7% of the healthy military population, making it a relatively uncommon error.[11] Lateral trunk lean may partially explain previously observed vertical ground reaction force asymmetry between the reconstructed and healthy limbs during drop landings.[9,10,17] The contralateral, or healthy, limb absorbs more force during landing, and this may be a potential avoidance strategy of the reconstructed limb.[9,10,17] Laterally flexing the trunk shifts the center of mass over the healthy limb and alters the mechanical and neuromuscular loading strategy, possibly influencing subsequent injury risk (ipsilateral or

Table 2. Landing Error Scoring System (LESS) Operational Definitions and Common Errors Between Groups[a]

LESS Item	LESS Score	Group Total, No. (%)		Fisher Exact Test P Value
		Control	Anterior Cruciate Ligament Reconstruction	
1. Knee-flexion angle at initial contact	Y = 0 N = 1	18 (67)	24 (89)	.09
2. Hip flexion at initial contact	Y = 0 N = 1	0 (0)	0 (0)	NA
3. Trunk-flexion angle at initial contact	Y = 0 N = 1	0 (0)	1 (4)	1.00
4. Ankle plantar-flexion angle at initial contact	Y = 0 N = 1	4 (15)	1 (4)	.35
5. Knee-valgus angle at initial contact	Y = 1 N = 0	20 (74)	20 (74)	1.00
6. Lateral trunk-flexion angle at initial contact	Y = 1 N = 0	5 (19)	17 (63)	.002[b]
7. Stance width—wide	Y = 1 N = 0	14 (52)	18 (67)	.40
8. Stance width—narrow	Y = 1 N = 0	0 (0)	1 (4)	1.00
9. Foot position—toe in	Y = 1 N = 0	0 (0)	2 (7)	.49
10. Foot position—toe out	Y = 1 N = 0	9 (33)	8 (30)	1.00
11. Symmetric initial foot contact	Y = 0 N = 1	4 (15)	3 (11)	1.00
12. Knee-flexion displacement	Y = 0 N = 1	0 (0)	0 (0)	NA
13. Hip-flexion displacement	Y = 0 N = 1	0 (0)	2 (7)	.49
14. Trunk-flexion displacement	Y = 0 N = 1	4 (15)	5 (19)	1.00
15. Knee-valgus displacement	Y = 1 N = 0	22 (81)	20 (74)	.74
16. Joint displacement	Soft = 0	4 (15)	4 (15)	.36
	Average = 1	23 (85)	20 (74)	
	Stiff = 2	0 (0)	3 (11)	
17. Overall impression	Excellent = 0	2 (7)	1 (4)	.14
	Average = 1	19 (70%)	15 (55%)	
	Poor = 2	6 (22%)	11 (41%)	

Abbreviations: N, no; NA, not applicable; Y, yes.

[a] Adapted from Padua et al.[11] Values are the number (percentage) of individuals who scored errors on at least 2 of the 3 trials.

[b] Statistically significant difference at $P < .0029$.

contralateral limb).[18] Alternatively, abnormal trunk positioning could be related to decreased trunk neuromuscular control, which has been associated with increased risk of primary ACL injury.[19] Zazulak et al[19] observed that lateral trunk displacement after an unexpected sudden force release predicted ACL injury risk in females. Although we did not measure trunk neuromuscular control, our sample was predominantly female, and trunk neuromuscular control is theorized to be an important component of second ACL injury prevention.[20]

Another possible explanation for the lateral trunk shift is *quadriceps arthrogenic muscle inhibition*, which is defined as persistent reflexive weakness of the quadriceps muscle after trauma or injury despite lack of damage to the nerve or muscle.[21] Postsurgical arthrogenic muscle inhibition and weakness of the quadriceps is described as *quadriceps avoidance* and results in decreased knee-extension moment and knee-flexion angle during activity.[22] Both of these factors are important to injury prevention, as landing from a jump requires a significant eccentric quadriceps contraction and knee-extension moment, and injury-prevention programs often focus on increasing knee flexion during landing.[23] Arthrogenic muscle inhibition does not seem to be influenced by graft choice, with authors reporting deficits in patients with patellar tendon[24,25] and hamstrings grafts.[26] With these factors in mind, rehabilitation after ACLR should focus on trunk neuromuscular control, core strength, equal force distribution between limbs, and quadriceps activation during landing, and these components should be evaluated before return to sport.

Our findings disagree with those of previous researchers who used advanced motion analysis to investigate kinematic differences between ACLR and control groups. Delahunt et al[8] observed differences in frontal and rotational femoral motion, as well as knee frontal-plane motion, between groups ranging from 2° to 6°. Other investigators have noted differences in hip adduction (2° difference)[7] and hip flexion (7° difference)[27] between groups. The design of the LESS is the most logical explanation as to why we did not observe any differences between groups in lower extremity motion. For most items, the LESS allows only for binary yes/no grading for the presence or absence of an error, which improves reliability[28] but does not allow a rater to assign a numeric value to a movement. It would be impossible to identify a 2° difference in hip adduction during a dynamic task without the aid of motion analysis. Furthermore, small differences in kinematics (less than 5°) would most likely not increase an individual's likelihood of making an error for most LESS grading items. The LESS is designed to document gross movement patterns associated with ACL loading, but it is not intended to identify small changes in movement that can be detected with traditional motion analysis. Although the LESS has been validated against traditional motion analysis, the advantage is that it can be administered in the field or clinic setting with limited resources and without specialized equipment and can be used for screening.

Current activity level was used as a covariate in our analysis because this factor differed between groups (Table 1). We believed it was more appropriate to account for current activity level because of the well-documented reduction in activity after ACLR.[29,30] In fact, previous authors have shown that the knee function (IKDC) score remains high within 6 years after reconstruction but that activity level significantly decreases,[29] with only 44% of ACLR patients returning to competitive sporting activity.[30] However, the ACLR population in our study had higher levels of activity than controls, which indicates that this population is still active and may have returned to sports. Our ACLR group was matriculating through college at the time of testing, and participants reported that most injuries occurred in high school. Age and change in team-participation status may have been significant contributing factors to their current activity levels. Our data support the notion that activity level did not have a major influence on movement quality as measured by the LESS. This idea is supported by the findings of Padua et al,[11] who initially validated the biomechanical profile of the LESS in a military population. Despite the highly active lifestyle of this population, 36% of women and 23% of men had more than 6 errors on the LESS, which classified their movement quality as poor. Our ACLR group still had a relatively high level of activity, and this highlights the predicament facing these athletes: they wish to return to sports but tend to perform activities associated with ACL injury poorly. The LESS may be useful for identifying and correcting compensatory movement patterns before return to sport.

Individual errors during a landing, rather than total score, may ultimately be more important to the risk of ACL injury. For example, 2 people with a total LESS score of 5 might have used different movement strategies to reach the same final score. One patient may have movement patterns with substantial frontal- and rotational-plane motion, whereas a second patient has the movement errors because of sagittal-plane deficiencies. Both individuals have the same total LESS score, but they may not represent the same landing strategy or injury risk. Beutler et al[13] observed that the combination of movement errors resulting in the total LESS score differed between sexes. Females were more likely to have decreased hip and knee flexion at initial contact and greater knee valgus, to land with a wider stance, and to have less knee displacement during landing.[13] Males were more likely to land with toes out and heels first and to have an asymmetrical foot landing.[13] Lateral trunk lean was not a common error identified in males or females, which may mean that it is an error specific to ACLR populations. Efforts are currently focused on shortening and removing nonessential LESS items. However, we recommend using the traditional LESS in ACLR patients until future researchers can identify which items are most relevant to this population. It is possible that high-risk LESS profiles differ between healthy and ACLR populations. It is also possible that any differences we observed could have existed before the initial ACL injury and persisted through reconstruction and rehabilitation. Several groups[4,31] have identified prospective neuromuscular risk factors for ACL injury, and rehabilitation strategies should focus on modifying these high-risk movement patterns after ACLR. High rates of second ACL injury after initial ACLR suggest that current return-to-participation criteria are inadequate in identifying who can safely and successfully return to high-risk activities.[4]

Clinical movement-assessment tools, such as the LESS, can assist with evaluation of jump-landing mechanics and provide valuable information when making return-to-sport decisions. The LESS can identify biomechanical deficiencies during landing, but further research is needed to determine which biomechanical deficiencies best predict injury and reinjury.[11,32] Future investigators need to determine if feedback or exercise interventions can successfully alter these landing mechanics in order to maximize use of the LESS in the rehabilitative process. The average IKDC 2000 subjective evaluation of knee function was 83.8% ± 10.4%, which is average in the literature.[33] However, future authors should determine what role this factor plays in predicting movement quality.

Our study had several limitations. We were unable to control for graft type but included the most common reconstruction procedures performed (patellar tendon, hamstrings, and allografts). The total LESS score was comparable among graft types (patellar tendon = 6.8 ± 2.3 errors, hamstrings = 6.3 ± 2.3 errors, allograft = 7.3 ± 0.9 errors), which supports the notion that the type of surgical procedure is not a significant contributing factor to the total LESS score. Our study was not powered to address this question, but emerging evidence suggests that allografts in young athletic populations may fail at a much higher rate than hamstrings and bone-patellar tendon-bone autografts.[34] We were also unable to control for specific rehabilitation protocols or recruit our population from a single therapy clinic due to the nature of our recruitment process. However, all participants described pursuing standard ACLR rehabilitation programs. Rather than matching limbs, we evaluated the injured limb in the ACLR group and the dominant limb in the control group. The total LESS score reflects whole-body mechanics and not degrees of movement-pattern dysfunctions. Because leg motions frequently mirror each other in the healthy population, it was appropriate to assess the dominant leg for the control group according to the LESS standard operating procedure. However, in the injured population, we theorized that the involved limb would exhibit more or different movement dysfunction than the healthy limb, so that leg should be graded to best reflect the overall, whole-body quality of motion. It is possible that this decision could have influenced our frequency analysis or led to unintentional bias during video evaluation. Finally, we were unable to control the time from surgery, but we used previously reported time restrictions to ensure that participants were within 7 years of reconstruction.[35]

We identified several trends in the LESS item frequency analysis that are worth noting. Specifically, 89% of individuals with ACLR received an error for landing with an extended knee at initial contact, compared with only 67% in the control group. Additionally, almost double the number of ACLR participants (n = 11) were classified as poor landers compared with healthy controls (n = 6). Our study was not powered to investigate differences in this secondary aim; however, future researchers should correctly power the FET to assess error frequencies in these variables to determine if they truly differ between groups.

CONCLUSIONS

Individuals with ACLR had higher total LESS scores than control participants and more often displayed lateral trunk lean toward the contralateral limb. These results may be partially explained by poor trunk neuromuscular control or quadriceps-avoidance strategies and should be areas of emphasis during rehabilitation. The LESS may be a useful clinical tool to aid in assessing motion in ACLR populations or clinically assessing landing mechanics before return to sport. The original LESS should be used in this population until more research can verify the LESS components that are most predictive of second ACL injury risk after ACLR.

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