The Landing Error Scoring System (LESS) Is a Valid and Reliable Clinical Assessment Tool of Jump-Landing Biomechanics

The JUMP-ACL Study

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Background: Anterior cruciate ligament injuries are common in athletes and have serious sequelae. A valid clinical tool that reliably identifies individuals at an increased risk for ACL injury would be highly useful for screening sports teams, because individuals identified as "high-risk" could then be provided with intensive prevention programs.

Hypothesis: A clinical screening tool (the Landing Error Scoring System, or LESS) will reliably identify subjects with potentially high-risk biomechanics.

Study Design: Cohort study (Diagnosis); Level of evidence, 2.

Methods: A jump-landing-rebound task was used. Off-the-shelf camcorders recorded frontal and sagittal plane views of the subject performing the task. The LESS was scored from replay of this video. Three-dimensional lower extremity kinematics and kinetics were also collected and used as the gold standard against which the validity of the LESS was assessed. Three trials of the jump-landing task were collected for 2691 subjects. Kinematic and kinetic measures were compared across LESS score quartiles using 1-way analysis of variance; LESS quartiles were compared across genders using the chi-square test. The LESS scores from a subset of 50 subjects were rescored to determine intrarater and interrater reliability.

Results: Subjects with high LESS scores (poor jump-landing technique) displayed significantly different lower extremity kinematics and kinetics compared with subjects with low LESS scores (excellent jump-landing technique). Women had higher (worse) LESS scores than men. Intrarater and interrater reliability of the LESS ranged from good to excellent.

Conclusion: The LESS is a valid and reliable tool for identifying potentially high-risk movement patterns during a jump-landing task.

Keywords: movement screen; ACL injury; jump-landing; injury risk

Movement patterns are important and modifiable factors that may influence the risk of ACL and other serious lower extremity injuries. Lower extremity movement patterns influence the load and deformational forces on ligaments.[8,15-17,22,23,28] Specific movement patterns commonly occurring during ACL and lower extremity injury include decreased sagittal plane joint flexion of the knee, hip, and trunk in combination with increased knee valgus and leg rotation.[10,21,24,37] Knee flexion angle greatly influences ACL loading as quadriceps contractions at low knee

flexion angles (0°-30°) can generate significant anterior tibial shear forces that facilitate high levels of ACL loading.[3,9,13,14] Isolated knee valgus and tibial rotation also cause ACL loading, but the magnitude of ACL loading is smaller compared with isolated anterior tibial shear force.[28] However, when knee valgus and tibial rotation are applied in combination with each other or with anterior tibial shear force, the amount of ACL load is greatly magnified.[8,22,23,28] To prospectively identify subjects at high risk for noncontact ACL injury, it may be necessary to assess for faulty movement patterns across multiple planes of motion based on research describing movement patterns during noncontact ACL injury events[10,24,37] and on research investigating ACL loading mechanisms.[8,15-17,22,23,28]

A prospective cohort study reported that women who displayed increased knee valgus angle and increased external knee valgus moments during a drop-landing task were at an increased risk of sustaining an ACL injury.[19] Although knee valgus angle and moment are identified as risk factors for ACL injury, this does not imply that isolated knee valgus is the primary ACL injury mechanism because isolated knee valgus does not facilitate sufficient load to injure the ACL without first causing medial collateral ligament injury.[7,15,28-30] Rather, knee valgus occurring in combination with other ACL loading mechanisms, such as anterior tibial shear force, may generate significant ACL loading between knee flexion angles of 0° and 40°.[28] The presence of faulty movement patterns in addition to knee valgus likely contributes to an elevated risk of noncontact ACL injury. Women have a higher incidence of ACL injury relative to men performing the same activities.[18] Thus, gender differences in sagittal plane and transverse plane motions at the hip and knee are also hypothesized to be potential risk factors for ACL injury. Potential risk factors in these planes include decreased knee flexion angle,[11,27,34] increased anterior tibial shear force,[12] decreased hip flexion angle,[11,25,26,34] increased hip internal rotation angle,[11] and increased knee internal rotation angle[31] during dynamic activities.

To identify subjects at high risk for ACL injury it is necessary to have a standardized tool for detecting the presence of multiple high-risk movement patterns. The Landing Error Scoring System (LESS) is an inexpensive clinical assessment tool that we developed to provide a standardized instrument; it uses 2 standard video cameras for identifying potentially high-risk movement patterns ("errors") during a jump-landing maneuver. Laboratory-based motion analysis systems are undoubtedly the gold standard for investigating biomechanical risk factors. However, because of time and cost constraints they are an impractical means to perform large-scale mass screenings with the goal of identifying subjects with high-risk movement patterns. To be feasible, a clinical assessment tool for high-risk landing mechanics should be brief, easily implemented as part of a large-scale team-screening session, and should provide a valid and reliable measure of landing biomechanics. We developed the LESS to meet this need.

The purpose of this study was to investigate the concurrent validity and reliability of the LESS. Laboratory-based 3-dimensional motion analysis was used as the gold standard against which we assessed the validity of the LESS. We hypothesized that the LESS would be able to distinguish between subjects with different joint kinematics and kinetics in the sagittal, frontal, and transverse planes of motion. In addition, we hypothesized that women (who are at higher risk of ACL injury) would have worse LESS scores compared with men.

MATERIALS AND METHODS

We collected LESS data on 2691 subjects who were incoming freshmen at the 3 large US military academies to compare 2 motion analysis systems: a sophisticated laboratory system (gold standard) and an inexpensive field analysis system (LESS) using 2 commercial video recorders. Each subject was analyzed simultaneously with the laboratory and field motion analysis systems. The kinematic and kinetic measures from the 3-dimensional motion analysis were used as the gold standard to assess the validity of the LESS. We also examined whether the LESS varied by gender, and established the intrarater and interrater reliability of the LESS using multiple raters for a subset of 50 subjects.

Participants

This study uses data from the first 2 years of enrollment in the JUMP-ACL (Joint Undertaking to Monitor and Prevent **ACL** Injury) study, a prospective study of biomechanical risk factors for ACL injury. There were 2691 participants (men: N = 1655, height = 178.29 ± 7.12 cm, weight = 77.54 ± 12.34 kg; women: N = 1036, height = 165.94 ± 6.63 cm, weight = 63.12 ± 7.88 kg) included in this study. Participants were incoming freshmen at the 3 largest US military academies who were deemed fit to participate in a physically demanding military training program and were preparing to participate in competitive collegiate or recreational varsity sports. Previous knee injury was not an exclusion criterion for participation in this study, but participants had to be healthy and free of orthopaedic injury at the time of testing. All subjects signed an informed consent form approved by multiple internal review boards before entering the JUMP-ACL study. Data were collected during July/August 2005 and July/August 2006.

Testing Procedures

The LESS data (inexpensive field analysis using 2 standard video cameras) and 3-dimensional motion analysis (gold standard) were collected simultaneously during a jump-landing task. The jump-landing task incorporated vertical and horizontal movements as participants jumped from a 30-cm high box to a distance of 50% of their height away from the box, down to a force platform, and immediately rebounded for a maximal vertical jump on landing (Figure 1). During task instruction, emphasis was placed on subjects jumping as high as they could once they landed from the box. Subjects were not provided any feedback or coaching on their landing technique unless they

Figure 1. The standardized jump-landing task consists of 2 segments: (1) subject jumps down from box and lands on ground and (2) subject immediately jumps vertically upward as high as possible.

were performing the task incorrectly. After task instruction, the subject was given as many practice trials as needed (typically 2) to perform the task successfully. A successful jump was characterized by (1) jumping off of both feet from the box; (2) jumping forward, but not vertically, to reach the force plate below; (3) landing with the entire foot of the dominant lower extremity on the force plate; (4) landing with the entire foot of the nondominant lower extremity off the force plate; and (5) completing the task in a fluid motion.

After task instruction and practice jumps (typically 2), electromagnetic tracking sensors were attached and digitization of the local segments and joint centers occurred. Participants performed 3 successful trials of the jump-landing task. Total testing time, including setup, was typically 5 minutes or less per subject.

Field-based Motion Analysis: Landing Error Scoring System (LESS). Two standard video cameras (DCR-HC38 MiniDV Handycam Camcorder, Sony Electronics, San Diego, California) captured a frontal plane and sagittal plane view of each subject as he or she performed the testing procedures. Figure 2 shows the specifications of the camera setup.

The LESS score is simply a count of landing technique "errors" on a range of readily observable items of human movement. A higher LESS score indicates poor technique in landing from a jump; a lower LESS score indicates better jump-landing technique. There are 17 scored items in the LESS. Table 1 (see online Appendix 1 for this article at http://ajs.sagepub.com/supplemental/) provides operational definitions and scoring details for each item. One set of items addresses lower extremity and trunk positioning at the time of initial contact with the ground (items 1-6). A second set of items assesses errors in positioning of the feet (items 7-11) and are scored at initial ground contact (item 11), at the time the entire foot is in contact with the ground (items 7 and 8), and between the time of initial contact and maximum knee flexion (items 9 and 10). A third set of items assesses lower extremity and trunk movements between initial contact with the ground and
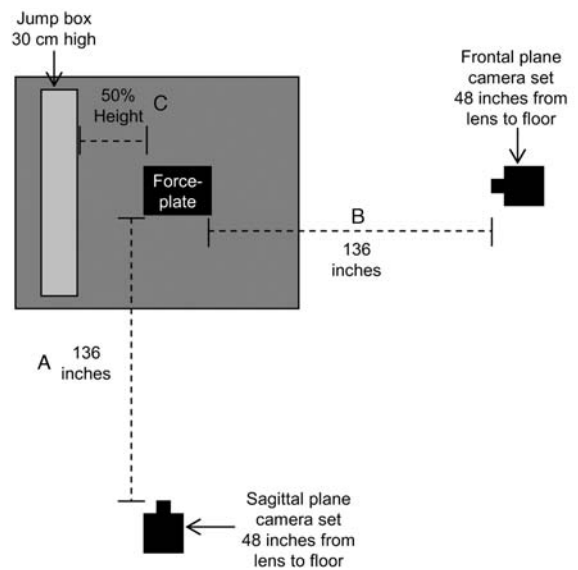

Figure 2. Camera placement during jump-landing task for LESS. A, 136 inches from camera to front of force plate; B, 136 inches from camera to side of force plate; C, 50% of subject's body height from jump box to force plate

the moment of maximum knee flexion angle (items 12-14) or the moment of maximum knee valgus angle (item 15). Finally, 2 "global" items address overall sagittal plane movement and the rater's general perception of landing quality (items 16 and 17).

Operationally, each test jump is videotaped (using 2 "off-the-shelf" camcorders) from both front and side views. The 2 videos are replayed at a later date and the LESS is scored during replay using pause and rewind controls. To simplify the scoring process, the rater focused on a designated "test leg," typically defined as the dominant leg. (We use the question, "Which leg do you refer to kick a ball with?" to establish leg dominance.) A trained rater requires 3 to 4 minutes to score 3 jump-landing trials per subject. The LESS scoring sheet is machine-readable

and was created using TeleForm software (Cardiff, Vista, California). Training materials and scoring sheets can be downloaded at www.unc.edu/sportmedlab/less.

Laboratory-based Motion Analysis. A Flock of Birds (Ascension Technologies, Inc, Burlington, Vermont) electromagnetic motion analysis system controlled by MotionMonitor software (Innovative Sports Training, Inc, Chicago, Illinois) was used to assess lower extremity kinematics at a sampling rate of 144 Hz. A nonconductive force plate (model 4060-NC, Bertec Corporation, Columbus, Ohio) was used to collect ground-reaction forces. Force plate data were collected synchronously with the kinematic data at a sampling rate of 1440 Hz. Previous research has reported that electromagnetic tracking systems provide accurate[2,35] and reliable[2] data for 3-dimensional movement of body segments and joints.

Electromagnetic sensors were placed on the subjects' skin over the L5 spinous process, lateral aspect of the thigh, and anteromedial aspect of the proximal tibia. Data indicating the orientation and position of each sensor relative to a standard range transmitter were conveyed back to a personal computer. Each sensor was placed over an area of the least muscle mass to minimize potential sensor movement and was secured using double-sided tape, prewrap, and athletic tape. Six bony landmarks were digitized with the end point of a stylus on which a fourth receiver was mounted. The 6 bony landmarks were the medial and lateral condyles of the femur, medial and lateral malleoli of the ankle, and left and right anterior superior iliac spine of the pelvis. Medial and lateral malleoli and femoral condyles were digitized to determine the ankle joint center and knee joint center, respectively. Left and right anterior superior iliac spine were digitized to determine the hip joint center of rotation using the Bell method.[6]

Data Processing and Reduction

Three-dimensional coordinates of lower extremity bony landmarks were estimated using MotionMonitor software. An embedded right-handed Cartesian coordinate system was defined for the shank, thigh, and pelvis segments to describe the 3-dimensional position and orientation of these segments. Euler angles were used to calculate the knee joint angle between the shank and thigh, and the hip joint angle between the thigh and pelvis in an order of rotations of (1) flexion-extension about the y-axis, (2) valgus-varus knee or adduction-abduction hip about the x-axis, and (3) internal-external rotation about the z-axis.

All kinematic data were filtered using a fourth-order low-pass Butterworth filter at 14.5 Hz. Kinematic and kinetic data were reduced using custom MATLAB software (MathWorks, Natick, Massachusetts). Three-dimensional peak knee and hip joint angles were determined at initial contact and during the stance phase of the jump-landing task. The stance phase was defined as the period between initial ground contact with the force plate until takeoff for the rebound jump. Initial ground contact was the time when vertical ground-reaction force exceeded 10 N as the subject landed on the force plate from the 30-cm high platform. Takeoff was identified as the time when vertical

ground-reaction force dropped below 10 N after initial contact. Additionally, displacement was calculated for lower extremity joint angles. This was calculated by subtracting the minimum joint angle during the stance phase from the maximum joint angle during the stance phase. The average of the peak values across the 3 trials was calculated for each of the kinematic and kinetic variables. Internal moments were normalized to body weight multiplied by height ($\times$ BW·H) and forces were normalized to body weight ($\times$ BW). The specific dependent variables analyzed were as follows: 3-D knee and hip joint angles at initial contact and peak over the stance phase, 3-D knee and hip joint angular displacement over the stance phase (peak angle – initial contact angle), peak 3-D knee and hip joint moments over the stance phase, peak anterior tibial shear force over the stance phase, and peak vertical and posterior ground-reaction force over the stance phase.

Statistical Analyses

On the basis of their LESS score, participants were divided into 4 quartiles, representing excellent (LESS score, $\leq$4), good (LESS score >4 to $\leq$5), moderate (LESS score >5 to $\leq$6), and poor (LESS score, >6) jump-landing biomechanics. Concurrent validity of the LESS was determined by comparing lower extremity kinematics and kinetics between groups and also by comparing LESS groups by gender using the chi-square test. A series of 1-way analysis of variance tests were performed for each lower extremity kinematics and kinetics variable, with group as the between-subject factor. Significant main effects were further analyzed using Tukey post hoc tests. A priori we expected that poor LESS scores would be associated with decreased knee and hip flexion angles, increased knee valgus angle and moment, increased anterior tibial shear force, and increased hip and tibial rotation.

To assess the intrarater and interrater reliability of the LESS, we randomly selected a subset of 50 subjects (25 men and 25 women) from the total subject pool. Intrarater reliability was assessed as a single rater (Rater 1) graded the LESS from the subgroup of subjects on 2 separate occasions. A minimum of 1 week separated the 2 grading sessions. Rater 1 was blinded to the original LESS scores during the second grading session. Interrater reliability was assessed by having a second rater (Rater 2), who was blinded to the LESS scores of Rater 1, grade the same subgroup of subjects previously scored by Rater 1 (LESS scores from first grading session). Intraclass correlation coefficient (ICC) and standard error of measure (SEM) values were determined to assess intrarater and interrater reliability using the ICC formula 2,1 and 2,k, respectively.

All data were analyzed using SPSS (version 15.0, SPSS Inc, Chicago, Illinois) with an a priori alpha level of .05.

RESULTS

The overall mean (SD) LESS score was 4.92 (1.67). The mean (SD) LESS score in the excellent, good, moderate, and poor groups were 2.71(0.88), 4.34 (0.27), 5.32 (0.28),
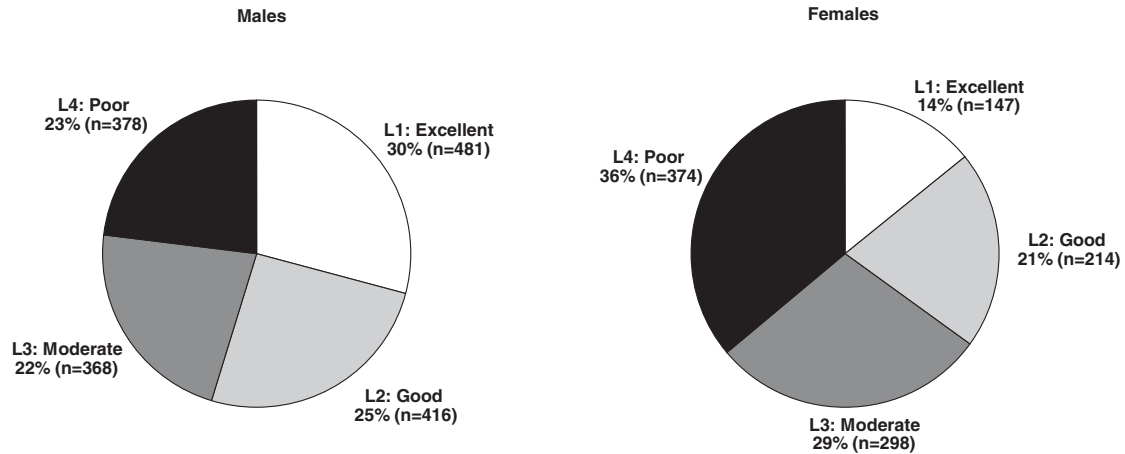
Males

Females

Figure 3. The LESS scores shown by gender.

6.91 (0.89), respectively. Women had worse LESS scores than men (Figure 3). Only 14% of women were in the excellent group, compared with 29% of men, whereas 36% of women were in the poor group, compared with 23% of men ($\chi^2 = 116.80$, $df = 3$, $P < .001$)

Descriptive statistics, F values, and P values for joint angles at initial contact, peak joint angles during stance, joint angular displacement over displacement, and peak moments and forces are presented in Tables 2 through 5, respectively (see online Appendices 2-5 for this article at http://ajs.sagepub.com/supplemental/). Statistical analyses comparing joint kinematics and kinetics between groups revealed significant group main effects for all lower extremity kinematics and kinetics variables, except for hip rotation angle at initial contact and hip adduction displacement during stance. Results from Tukey post hoc analyses are also presented in Tables 2 through 5 for the respective lower extremity kinematics and kinetics variables. Almost all lower extremity kinematics and kinetics examined were significantly different between those with different LESS scores. As expected, poor LESS scores were associated with decreased knee and hip flexion angle (sagittal plane kinematics), increased knee valgus and hip adduction angle (frontal plane kinematics), increased internal knee and hip internal rotation moment (transverse plane kinematics), increased internal knee and hip extension moment and anterior tibial shear force (sagittal plane kinetics), and increased internal knee valgus and hip adduction moment (frontal plane kinetics).

Some jump-landing biomechanics were significantly different between all groups (eg, peak knee flexion angle poor < moderate < good < excellent) and displayed large F values, while other variables had weaker gradients across the four LESS groups (eg, peak anterior tibial shear force poor > excellent, but no other differences between groups). Those variables displaying a stronger gradient across all groups include peak knee flexion angle and displacement, peak hip flexion angle and displacement, peak vertical ground-reaction force, peak knee valgus angle, and peak knee extension moment.

The $ICC_{2,k}$ and SEM values for interrater reliability were 0.84 and 0.71, respectively. These findings indicate that the LESS has good interrater reliability. Intrarater reliability for the LESS was excellent, as $ICC_{2,1}$ and SEM values were 0.91 and 0.42, respectively.

DISCUSSION

The LESS was designed as a clinical assessment tool to identify subjects displaying jump-landing biomechanics that potentially place them at risk for noncontact ACL injury. The most important finding of this study is that the LESS successfully distinguished between groups on a range of jump-landing biomechanics that have previously been shown to be related to ACL loading and injury mechanisms. There were significant differences in sagittal, frontal, and transverse plane biomechanics, and in vertical ground-reaction force, between subjects with poor (LESS score >6) and excellent (LESS scores ≤4) jump-landing technique. Women, who have a higher risk of ACL injury than men performing the same activities,[1] were more likely to score in the poor LESS score group. The LESS also demonstrated good interrater and intrarater reliability. Based on these findings, the LESS appears to be a valid and reliable clinical assessment tool for detecting poor jump-landing biomechanics.

Biomechanical risk factors for noncontact ACL injury are multiplanar in nature, and clinical assessment of jump-landing biomechanics should reflect this fact. Previous research using the drop-jump test as a possible clinical assessment tool has measured 2-dimensional knee valgus (angle or frontal plane knee separation distance)[4,5,33,36] and ground-reaction force.[20] However, noncontact ACL injury is considered to be multifactorial in nature[18] and probably involves multiple biomechanical risk factors acting in multiple planes. The LESS includes a more comprehensive assessment of multiplanar biomechanics than previous clinical assessments of poor jump-landing biomechanics.[4,5,20,33,36]

The importance of identifying multiplanar biomechanical risk factors for ACL injury was demonstrated in a prospective cohort study that indicated that subjects who went on to suffer ACL injury displayed different lower extremity biomechanics in both the sagittal and frontal planes.[19] Simulation models of noncontact ACL injury further underscore the importance of multiplanar joint biomechanics.[32] In a recent set of models, isolated sagittal plane loading did not increase the risk of simulated noncontact ACL injury; however, knee valgus moment combined with either decreased knee or decreased hip flexion, or decreased hip internal rotation velocity, did result in greater ACL injury risk.[32]

This study has shown that the LESS is a valid and reliable tool for the identification of subjects with landing errors in multiple planes. However, additional research is needed to determine the predictive ability of the LESS for noncontact ACL injury. In due course, the JUMP-ACL study will establish whether the LESS definitively predicts the risk of ACL injury in the military cadet population.

Reliability of the LESS

Our findings revealed good-to-excellent interrater and intrarater reliability, respectively, for the LESS. Also, the LESS appears to be a sensitive clinical assessment tool of jump-landing biomechanics as SEM values were less than 1 for both interrater and intrarater reliability measures. It is important to note that the raters who scored the LESS underwent a comprehensive training program. The training program begins with watching a PowerPoint presentation that described the importance of proper movement patterns and the potential for movement errors identified in the LESS to increase ACL load and subsequent injury risk. After completion of the presentation, the raters scored a model series of 20 subjects who were previously scored by an expert rater. Any discrepancies in LESS scores between raters were discussed and clarified between raters as part of their training.

We believe that proper training is critical for ensuring good interrater and intrarater reliability. Finally, an important issue for the reliability of the LESS is whether increasing the number of jumps per subject (3 in the JUMP-ACL study) would further improve the reliability of the mean LESS score. It was beyond the resources of this study to explore this question.

Limitations

One limitation of the LESS is its reliance on subject performance in a single type of jump-landing, a vertical drop jump from a 12-inch box. A concern is that many ACL injuries often involve significant forward momentum, in combination with complex movements such as side-cutting or cross-cutting, and may involve a cognitive perturbation (such as an unanticipated move by an opponent). These elements are not present in the vertical drop-jump task. The benefits of using the jump-landing or drop vertical jump tasks are that these tasks are relatively simple to learn and perform (low number of mistrials), require very little space to conduct, and can be completed in a timely manner for a large number of subjects.

The selection of a jump-landing task was based in part on previous research that incorporated similar tasks during clinical assessment of knee valgus and landing forces.[4,5,20,33,36] A recent International Olympic Committee current concepts statement on noncontact ACL injuries in female athletes recommended that a drop vertical jump type of task should be used to identify athletes at risk of severe knee injuries.[38] The jump-landing task used in this study was very similar to the drop vertical jump test recommended by the International Olympic Committee.

Even though the LESS is a valid and reliable clinical assessment tool for poor jump-landing biomechanics, we caution that the ability of the LESS to predict ACL injury was not addressed in this study. Future prospective research investigating the ability of the LESS to predict those who go on to sustain noncontact ACL injury is currently in progress. Because of its emphasis on capturing multiplanar movement, the LESS includes a relatively large number of items, and includes some items (such as toe-in-foot position) that were infrequently endorsed. Furthermore, there are correlations between some of the items. Future research will address these issues by determining whether meaningful "movement subscales" can be extracted from the LESS and assessing whether items that are nonpredictive of injury should be deleted. A further limitation is that the "cut points" used to divide LESS score into excellent, good, moderate, and poor in this study were based on quartiles of the overall LESS distribution and are therefore specific to our study population. We caution that these cut points should not be automatically applied to other populations.

CONCLUSION

We performed this study to determine whether a clinical assessment tool of jump-landing movement patterns (LESS) could be used as a valid and reliable indicator of poor lower extremity biomechanics. Subjects with poor (high) LESS scores demonstrated different lower extremity kinematics and kinetics across multiple biomechanical factors and in multiple planes of motion. Those with poor jump-landing technique demonstrated less knee and hip flexion motion, more knee valgus and hip internal rotation motion, greater knee joint loading (anterior tibial shear force, knee extension moment, knee valgus moment), and greater vertical ground-reaction force. The LESS demonstrated good-to-excellent interrater and intrarater reliability. On the basis of these findings the LESS is a valid and reliable assessment of overall jump-landing biomechanics that considers multiplanar movement patterns. Potentially, the LESS may be a useful clinical assessment tool to use during large-scale screening to identify those at risk for noncontact ACL injury and other serious lower extremity injury.

ACKNOWLEDGMENT

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