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ORIGINAL

Integrating the Landing Error Scoring System and OpenCap for Anterior Cruciate Ligament Injury Risk Assessment in Female Basketball Players: A Preliminary Study

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Objective: The purpose of this study was to objectively identify common landing errors in female basketball players by integrating the Landing Error Scoring System (LESS) with OpenCap.

Method: Eleven collegiate female basketball players were recruited to perform a LESS jump landing task from a 30 cm high box. Landing mechanics were recorded using two iOS devices via OpenCap. A modified full-body musculoskeletal model was used in conjunction with OpenSim's inverse kinematics to objectively quantify landing mechanics, including multi-planar knee joint motion.

Results: The mean LESS was 5.64 ± 0.77, placing the participants in the moderate category of landing mechanics. The most frequently observed error was knee valgus displacement (LESS item 15), present in all participants. Joint displacement (LESS item 16) and knee valgus angle at initial contact (LESS item 5) were also prevalent, observed in 90.91% and 81.82% of participants, respectively. Based on LESS score distributions, 55% of participants categorized as having moderate landing mechanics, 27% as good, 9% as poor, and 9% as excellent.

Conclusion: The results of our study indicate that targeted interventions may be necessary to reduce Anterior Cruciate Ligament (ACL) injury risk among female basketball players. Integrating LESS scores with OpenCap provides a practical and accessible approach to identifying key biomechanical risk factors associated with ACL injury.

Keywords: Anterior Cruciate Ligament (ACL) injury, Landing Error Scoring System (LESS), OpenCap, Female basketball players

INTRODUCTION

Anterior cruciate ligament (ACL) injury is prevalent among young athletes and is considered one of the most debilitating injuries, especially in athletes participating in high-impact sports such as basketball (Agel et al., 2007; Deitch, Starkey, Walters & Moseley, 2006; Leppanen et al., 2017; Munro, Herrington & Comfort, 2012; Taylor et al., 2017). The economic impact

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of ACL injuries is significant, with the direct costs of surgical procedures and rehabilitation ranging from $17,000 to $25,000 per injury (Hewett, Lindenfeld, Riccobene & Noyes, 1999; Loes, Dahlstedt & Thomée, 2000). Considering the potential losses, including loss of scholarships, professional opportunities, as well as an increased risk of osteoarthritis, the long-term costs could impose a significant economic burden on individuals and society. To mitigate these burdens, cost-effective and field-deployable screening tools that can provide objective data are needed, particularly among high-risk populations. Notably, female athletes who participate in pivoting and jumping sports such as basketball have a four to sixfold greater incidence of ACL injury compared to their male counterparts (Agel et al., 2007; Arendt & Dick, 1995; Deitch et al., 2006; Malone, 1992; Munro et al., 2012; Myklebust et al., 2003). Therefore, greater attention should be directed toward identifying sex-specific risk factors and incorporating them into clinical decision-making processes.

Functional tests and other assessment tools have been widely used to screen for injury risk and to guide individualized interventions (Brown, Ko, Rosen & Hsieh, 2015; de la Motte, Arnold & Ross, 2015; Hertel, Braham, Hale & Olmsted-Kramer, 2006; Rosen, Needle & Ko, 2019; Zwolski, Schmitt, Thomas, Hewett & Paterno, 2016). Among these, the Landing Error Scoring System (LESS) is frequently employed to identify movement patterns associated with ACL and other lower extremity injuries (Beese, Joy, Switzler & Hicks-Little, 2015; Bell, Smith, Pennuto, Stiffler & Olson, 2014; Hanzlikova, Athens & Hebert-Losier, 2020, 2021; Morooka et al., 2023; Padua et al., 2009). The LESS is relatively quick and inexpensive to administer, however, its scoring process requires trained raters to visually inspect video recordings or live performance, which may introduce variability and reduce accuracy (Padua et al., 2009).

To overcome some of these limitations of observational assessments, various studies have used three-dimensional (3D) motion capture systems to collect more precise kinematic data. However, the application of such systems is often restricted by spatial constraints and high costs. A markerless motion capture system, OpenCap, has offered a viable alternative. OpenCap integrates deep learning algorithms with cloud-based musculoskeletal modeling to generate 3D kinematics from videos recorded by as few as two smartphone cameras (Uhlrich et al., 2023; Verheul, Robinson & Burton, 2024). Prior validation studies reported that OpenCap can estimate joint angles and moments with mean absolute errors of approximately 4-5° and 1.2% body weight×height, respectively, achieving accuracy comparable to marker-based 3D motion capture systems (Turner, Chaaban & Padua, 2024; Uhlrich et al., 2023). These findings indicate that OpenCap may serve as a practical tool for conducting field-based assessments. Although OpenCap shows promise, it has not yet been systematically integrated with established clinical assessment tools such as the LESS, and the use of the integrated approach among female basketball players remains limited.

Therefore, the purpose of this study was to objectively identify common landing errors among female basketball players by integrating the LESS with OpenCap. This combined approach is expected to offer a more accessible means of assessing ACL injury risk and may contribute to the development of practical, field-based screening protocols that help reduce the personal and economic burdens associated with such injuries.

METHODS

1. Participants

Eleven collegiate female basketball players participated in this study (n = 11, age = 21.27±1.10 yrs, height = 166.27±8.15 cm, mass = 59.25±8.37 kg). Participants were included if they were free from lower extremity injury and had no history of lower extremity injury within the six months prior to data collection. All participants read and signed an approved informed consent document prior to data collection.

2. Experimental procedure

The jump landing task was based on the methodology outlined by Padua et al. (Padua et al., 2009). Participants jumped from a 30 cm high box, landing on both feet at a target set at 50% of each participant's height from the box. Following the setup described in Uhlrich et al. (Uhlrich et al., 2023), two iOS devices were mounted on tripods at a height of 1.2 meters and positioned around the participants (Figure 1). Three-dimensional kinematic data were collected using the cloud-based OpenCap platform.

3. Musculoskeletal modeling and analysis

Video recordings from the two iOS devices were uploaded

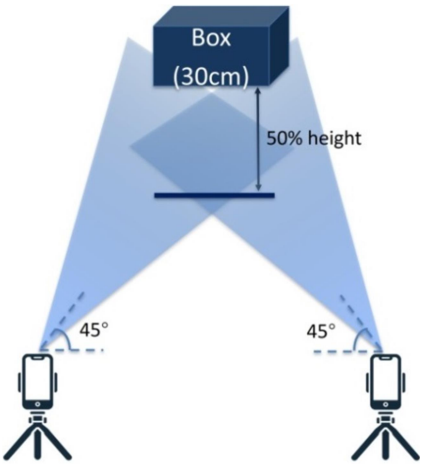

Figure 1. Schematic representation of the LESS setup with two iOS devices for data collection.

and processed in OpenCap to estimate joint kinematics using a full-body musculoskeletal model (Lai, Arnold & Wakeling, 2017; Rajagopal et al., 2016). Following data collection, OpenCap files for each LESS trial were downloaded for subsequent offline analysis. The offline analysis involved two primary procedures. Initially, the musculoskeletal model's knee joint was modified by adding two additional degrees of freedom. This modification enabled a more precise representation of knee joint motion in the frontal and transverse planes, which is

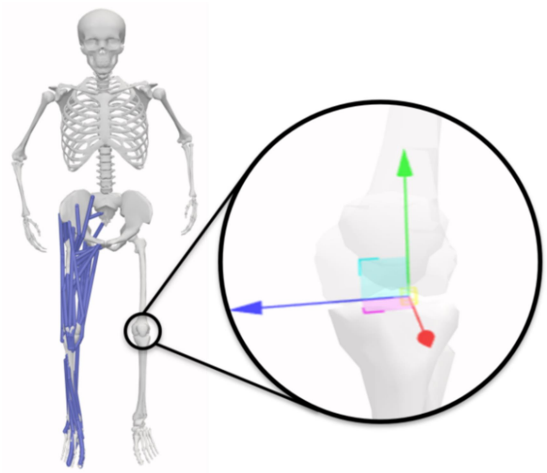

Figure 2. Musculoskeletal model with a three degree-of-freedom knee joint: (1) Flexion-extension (depicted by a blue horizontal arrow); (2) Varus-valgus (depicted by blue a red arrow); (3) Internal-external rotation (depicted by a green arrow)

particularly important for LESS scoring (Figure 2). Second, joint angles from the recorded LESS trials were calculated using OpenSim's inverse kinematics tool.

4. LESS scoring

For LESS scoring, angles for knee flexion, hip flexion, trunk flexion, plantar flexion, knee valgus, and lateral trunk flexion were calculated using OpenSim's inverse kinematics tool. These measurements were then used to score LESS items 1 through 7 at initial contact. Stance width, relevant to LESS items 8 and 9, was calculated using the acromion and lateral malleolus markers on the scaled musculoskeletal model, which were then used to classify the stance as either wide or narrow. Foot positioning for LESS items 10 and 11, indicating external and internal rotation, was determined from the subtalar angle. The symmetry of initial foot contact (LESS item 12) was evaluated by measuring the vertical height difference between toe markers, with a difference of less than 4 cm considered symmetrical. The velocity upon landing from a height of 30 cm was calculated using the free fall formula, yielding 2.43 m/s. Given the data collection frequency of 60 Hz, the potential measurement variability was determined to be 4.03 cm. Therefore, a 4 cm cutoff was chosen to accommodate this potential variability.

The displacement of knee, hip, and trunk flexion angles from initial contact to the point of maximum knee flexion (LESS items 13-15) was also calculated using results from OpenSim's inverse kinematics tool. The criteria for determining landing softness (LESS item 16) were adapted from a previous study (Devita & Skelly, 1992), with a knee angle of less than 77° classified as a stiff landing, between 77° and 117° classified as an average landing, and greater than 117° classified as a soft landing.

For LESS item 17, we adopted criteria tailored to bilateral jump landings, informed by a study (Kristianslund, Faul, Bahr, Myklebust & Krosshaug, 2014) on knee valgus, lateral trunk flexion, and trunk rotation during side cutting in female volleyball athletes, however we used more conservative thresholds given the nature of the movement under investigation:

i. Excellent (score 0): All angles (knee valgus, torso lateral flexion, and torso rotation) were less than 5°.
ii. Average (score 1): At least one angle ranged between 5° and 10°.
iii. Poor (score 2): At least one angle exceeded 10°

RESULTS

It is important to acknowledge that the LESS scoring criteria differ depending on the specific item. For certain items, an error is recorded when the expected movement criterion is met (Yes), whereas for others, an error is assigned when the criterion is not met (No).

Table 1. Landing Error Scoring System (LESS) item-level scores and total score (mean ± SD)

LESS item	Mean (SD) of LESS score
1. Knee flexion angle at initial contact: greater than 30° Yes = 0, No = 1	0.09 (0.29)
2. Hip flexion angle at initial contact: hips are flexed Yes = 0, No = 1	0.00 (0.00)
3. Trunk flexion angle at initial contact: trunk in front of hips Yes = 0, No = 1	0.00 (0.00)
4. Ankle plantar flexion at initial contact: greater than 0° Yes = 0, No = 1	0.18 (0.39)
5. Knee valgus angle at initial contact: greater than 0° Yes = 1, No = 0	0.82 (0.39)
6. Lateral trunk flexion at initial contact Yes = 1, No = 0	0.00 (0.00)
7. Stance width-wide: > shoulder width Yes = 1, No = 0	0.09 (0.29)
8. Stance width-narrow: < shoulder width Yes = 1, No = 0	0.09 (0.29)
9. Foot position: external rotation: > 30° Yes = 1, No = 0	0.00 (0.00)
10. Foot position: internal rotation: > 30° Yes = 1, No = 0	0.00 (0.00)
11. Symmetric initial foot contact: less than 4 cm difference Yes = 0, No = 1	0.00 (0.00)
12. Knee flexion displacement: > 45° Yes = 0, No = 1	0.73 (0.45)
13. Hip flexion displacement: greater than at initial contact Yes = 0, No = 1	0.18 (0.39)
14. Trunk flexion displacement: greater than at initial contact Yes = 0, No = 1	0.00 (0.00)
15. Knee valgus displacement: peak knee valgus angle greater than initial contact Yes = 1, No = 0	1.00 (0.00)
16. Joint displacement Soft = 0, Average = 1, Stiff = 2	1.18 (0.39)
17. Overall impression Excellent = 0, Average = 1, Poor = 2	1.27 (0.75)
Group Mean	5.64 (0.77)

1. LESS score

LESS scores are shown in Table 1. The overall mean LESS score for the participants was 5.64±0.77. LESS item 15 (knee valgus displacement) had the highest mean score (1.00±0.00). LESS item 5 (knee valgus angle at initial contact) had a mean score of 0.82±0.39. LESS item 12 (knee flexion displacement: >45°) showed a mean score of 0.73±0.45. LESS items 4 (ankle plantar flexion at initial contact) and 13 each scored 0.18±0.39. LESS items 7 and 8 each scored 0.09±0.29. For items with a scoring range of 0 to 2, LESS item 16 (joint displacement) had a mean score of 1.18±0.39, and LESS item 17 (overall impression) had a mean score of 1.27±0.75.

2. Frequency and percentage of common landing errors

Frequency and percentage of common landing errors are shown in Figure 3. The most frequent landing error was LESS item 15 (knee valgus displacement), observed in all participants (100%). LESS item 16 (joint displacement) occurred in 10 participants (90.91%), and LESS item 17 (overall impression indicating poor to average landing mechanics) appeared in 9 participants (81.82%). LESS item 5 (knee valgus at initial contact) was noted in 9 participants (81.82%).

LESS item 12 (knee flexion displacement >45°) was observed in 8 participants (72.73%). LESS items 4 (ankle plantar flexion at initial contact) and 13 (hip flexion displacement) each occurred in 2 participants (18.18%). LESS items 1 (knee flexion angle at initial contact >30°), 7 (stance width-wide), and 8 (stance width-narrow) were each seen in 1 participant (9.09%).

3. Distribution of LESS scores

Participants were classified into four categories based on their LESS scores: excellent (≤4), good (>4 to ≤5), moderate (>5 to ≤6), and poor (>6) (Padua et al., 2009). The distribution was as follows: moderate (55%, n = 6), good (27%, n = 3),

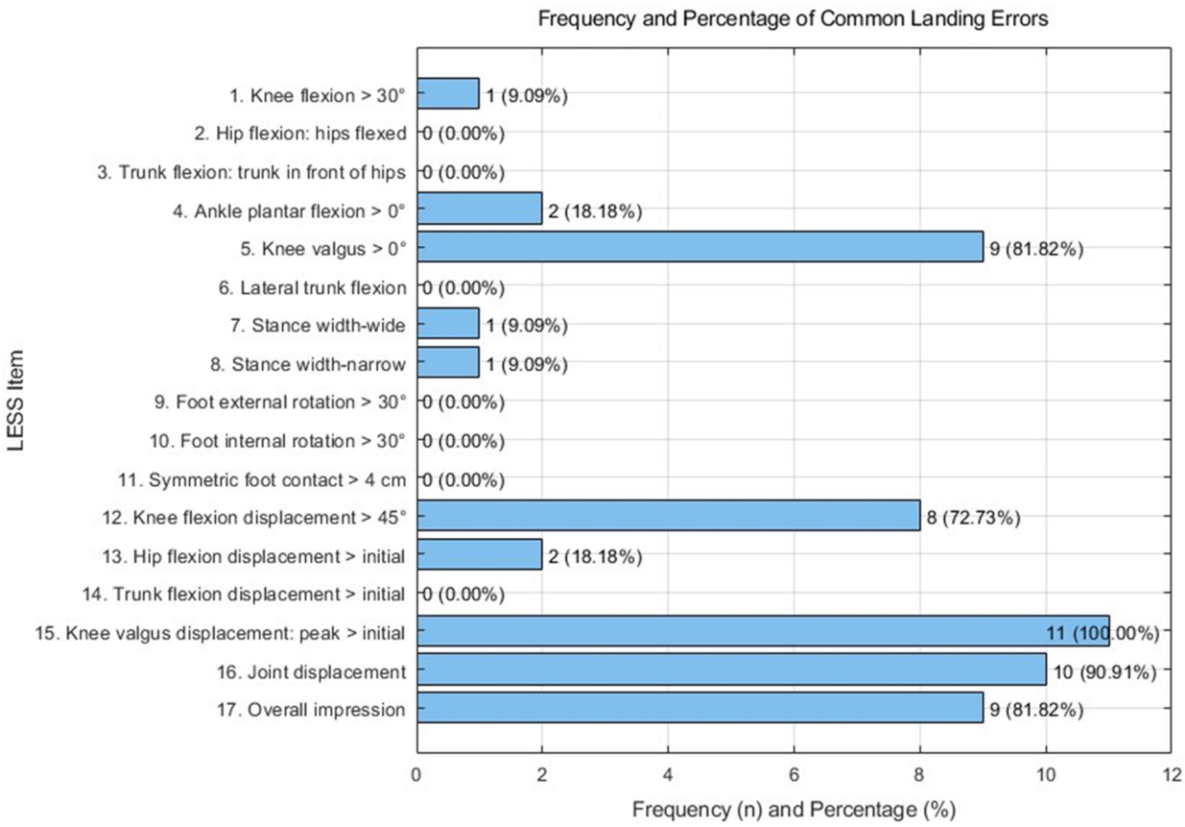

Figure 3. Frequency and percentage of common landing errors in female basketball players

excellent (9%, n = 1), and poor (9%, n = 1) (Figure 4).

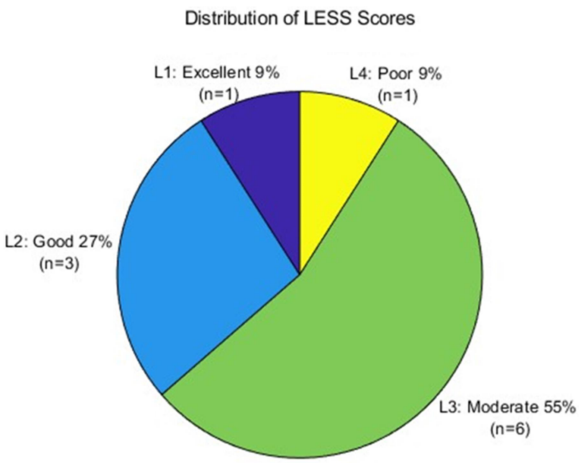

Figure 4. Pie chart representation of LESS score distribution

DISCUSSION

The purpose of this study was to improve injury risk assessment in female basketball players by integrating the LESS with OpenCap. This combined approach not only has the potential to provide more accurate and objective evaluations of landing mechanics associated with ACL injury risk but also demonstrates how the LESS and OpenCap can be applied to identify landing errors related to ACL and other lower extremity injuries.

The mean LESS score observed in this study (5.64±0.77) was similar to that reported in a previous study (6.00±2.13) involving female basketball players (Lisman, Wilder, Berenbach, Jiao & Hansberger, 2021). These results suggest that female basketball players may have a moderate level of landing errors. However, it is important to acknowledge that the prior study used a modified LESS rubric which included 22 items but excluded two subjective items, resulting in a maximum score of 21. In contrast, this study used the original 17 item rubric with a maximum score of 19. This methodological difference may partially account for variations in total LESS scores and should be considered when making comparisons across studies.

Knee valgus displacement (LESS item 15) was the most frequent landing error, observed in all participants. Previous studies have identified dynamic knee valgus as a significant risk factor for ACL injury (Deitch et al., 2006; Hewett et al., 2005; Hewett, Myer, Ford, Paterno & Quatman, 2016; Quatman et al., 2014). The second most common error was joint displacement (LESS item 16), observed in 90.91% of participants. This result indicates that the participants did not demonstrate sufficient flexion at the hip, knee, and ankle joints during landing. Such stiff landing mechanics may elevate impact forces, thereby increasing the load transferred to passive structures, including ligaments, cartilage, and joint capsules (Hewett et al., 2016). When combined with dynamic knee valgus, this stiff landing strategy may substantially increase the risk of ACL injury (Larwa, Stoy, Chafetz, Boniello & Franklin, 2021; Tamura et al., 2017). The overall impression scores (LESS item 17) indicated that 81.82% of the participants exhibited average to poor landing mechanics. Collectively, our findings indicate that dynamic knee valgus, insufficient joint displacement, and excessive frontal plane movement should be prioritized as key targets in ACL injury prevention for female basketball players (Hewett, Ford & Myer, 2006; Hewett et al., 2005; Hewett et al., 2016). It is important to develop clinical assessment tools that can quantify these movement deficits accurately and reliably (Myers et al., 2011). Therefore, we developed an integrated approach that identifies movement patterns associated with ACL injury. This combined approach supports continuous monitoring and may allow early detection of recurrent movement deficits that can be modified through targeted interventions. In practice, this simple setup allows practitioners to screen an entire team on the court using only two smartphones and the LESS checklist. Following screening, athletes demonstrating suboptimal landing mechanics can receive immediate corrective feedback.

Approximately two-thirds of the participants in this study were classified within the moderate to poor landing mechanics category. Similarly, previous research has found that both injured and noninjured female basketball players had average LESS scores of 7 and 8, which fall within the poor landing category (Siupsinskas, Garbenyte-Apolinskiene, Salatkaite, Gudas & Trumpickas, 2019). Although our participants had no recent history of injury, their moderate-to-poor LESS scores indicate that they may still have underlying movement patterns that could increase their risk of ACL injury. Therefore, improving landing mechanics may be an important component in reducing the risk of lower extremity injuries in this population.

There were several limitations in this study. First, our sample included only female basketball players. While aligned with our aims, this focus may limit generalizability. Future studies should include a broader range of participants to verify that the bene-

fits of this combined approach hold across sexes and sports. Second, although OpenCap has demonstrated good validity for measuring lower limb kinematics during jump landing tasks, minor measurement errors or misestimations can occur especially if video quality or camera positioning is suboptimal. We mitigated this by following established OpenCap setup protocols, but subtle inaccuracies in joint angle estimation cannot be entirely ruled out. Third, the LESS does not explicitly specify precise thresholds to distinguish between "soft," "average," and "stiff" for LESS item 16 (joint displacement), and "large," "average," and "poor" for LESS item 17 (overall impression). Although we followed the criteria used in previous studies, the lack of universal thresholds for these items may affect scoring consistency. Finally, we assessed biomechanical risk factors at a single time point and did not track whether basketball players who scored poorly, eventually sustained ACL injuries. Prospective longitudinal studies are needed to determine whether interventions informed by the LESS and OpenCap ultimately reduce ACL injury risk.

Despite these limitations, this study presents several distinct strengths. First, we utilized musculoskeletal models to calculate joint kinematics more accurately. Specifically, we added two degrees of freedom to the knee joint to describe frontal and transverse plane motion, which is closely linked to ACL injury risk. Second, we aimed to enhance the objectivity of the LESS by quantifying items 16 and 17, which are typically scored subjectively. The use of measurable criteria for these items may help improve consistency in the assessment process across raters. Future work should refine and standardize these criteria to support more reliable LESS assessment.

CONCLUSION

This study integrated the LESS with OpenCap to objectively evaluate movement patterns associated with ACL injury risk in female basketball players. We observed dynamic knee valgus, insufficient joint displacement, and excessive frontal plane movement, all of which have been associated with an increased risk of ACL injury. Targeted interventions appear to be necessary to address the identified deficits and reduce ACL injury risk in female basketball players. Future research is needed to evaluate whether the integrated approach and the targeted interventions it informs improve landing mechanics and reduce ACL injury risk. A larger and more diverse sample, including athletes from diverse sports, would also enhance the generalizability of these results and provide insight into sport-specific landing mechanics related to ACL injury risk.

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