Reliability and Construct Validity of the Single-leg Landing Error Scoring System (SL-LESS) in Physically Active Females

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DOI: [https://doi.org/10.25035/jsmahs.09.02.03](https://doi.org/10.25035/jsmahs.09.02.03)  
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Reability and Construct Validity of the Single-Leg Landing Error Scoring System (SL-LESS) in Physically Active Females

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Purpose: Single-leg landings are common in sport and often result in injury, however a rubric to evaluate biomechanics during single-leg jump landing (SLL) does not exist. The Single-Leg Landing Error Scoring System (SL-LESS) is a rubric developed to evaluate movement during SLL. The purpose of this study was to 1) determine inter- and intra-rater reliability of the SL-LESS, 2) and determine the content and construct validity of the SL-LESS when evaluating SLL. Method 28 healthy females completed SLL on two days while 2D and 3D data were recorded. 3D angles were trunk flexion/lateral-flexion, pelvic tilt/contralateral drop, hip flexion/adduction, and knee flexion/abduction at initial contact (IC) and maximum knee flexion (MKF). Two raters used the SL-LESS rubric to score 2D videos each day. Participants were grouped by total SL-LESS score (≤ 2 errors=good; ≥4 errors=poor landers). Kappa, prevalence- and bias-adjusted kappa (PABAK), and percent agreement were calculated for inter- and intra-rater reliability between rubric items. Total score reliability was evaluated using an ICC. Differences in 3D angles, knee abduction moment(KABDM), and vertical ground reaction force(vGRF)between good and poor landers were evaluated using a one-way ANOVA (construct validity). p<.05. Results SL-LESS item inter-rater (Average κ=0.21±0.21, PABAK=0.60±0.28, % agreement=0.78±0.13); and intra-rater (Average K=0.30±0.21, PABAK=0.60±0.21, %agreement= 0.79±0.12) reliability were moderate. Inter-(ICC(2,1)=0.50) and intra-rater (ICC(3,1)=0.56) reliability for total score were moderate. Good landers displayed significantly greater hip and trunk flexion at IC, and hip and knee flexion at MKF, lower KABDM at initial contact, and lower vGRF (p<.05) compared to poor landers, so it is valid to detect “stiff” landers. Conclusions The SL-LESS can reliably be used to evaluate the SLL movement and can discriminate between “stiff” landings with upright posture and high impact force from “soft” landings with flexed landing posture with lower impact force. Key Words: unilateral, jump landing, assessment, biomechanics, movement

INTRODUCTION

Abnormal loading of knee structures due to poor limb alignment during dynamic tasks is a major contributor to knee injury risk. 1-4 The abnormal movement pattern is commonly called dynamic valgus and consists of contralateral pelvic drop, with ipsilateral hip adduction and internal rotation, knee abduction, tibial internal rotation, and foot pronation.2,3,5,6 Clinicians evaluate movement quality during tasks such as jump-landing to identify modifiable movements that may be related to injury risk.2,3,7 Although three-dimensional motion analysis (3DMA) yields precise information about joint angles and loading, it may not be feasible for clinical settings due to high cost and expertise requirements. Movement evaluation using 2D motion analysis (2DMA) or rubric assessment has greater feasibility in clinical settings.

The majority of acute knee injuries occur during single-leg tasks such as landing, decelerating, or cutting.8-13 However, most assessments of lower extremity biomechanics use a double-leg jump landing (DLL) task.14-17 There are significant differences in biomechanics between double-leg and single-leg landings.18,19 During a single-leg jump landing (SLL) the participant stands on a single-leg on a box, jumps forward to land in a target on the floor, and performs a maximal vertical jump.20-23 The SLL demands high neuromuscular control and coordination, especially at the knee and trunk, and produces
greater impact forces than a DLL.\textsuperscript{10,18,24,25} Therefore, clinicians could gain valuable information by evaluating SLL biomechanics using a standardized, clinician-friendly assessment.

Recent systematic reviews concluded that 2DMA is reliable in the evaluation of DLL and single-leg squats.\textsuperscript{26,27} However no studies on rubric assessments of SLL were found. The most widely used rubric assessment for the DLL task is the Landing Error Scoring System (LESS). The LESS is an 17-item, rubric assessment that is scored by reviewing 2DMA videos from the frontal and sagittal planes, and is a reliable and valid method of evaluating movement during a DLL task.\textsuperscript{12,14-17} There is a need for a rubric assessment to evaluate the SLL so clinicians and researchers can most comprehensively evaluate movement during jump landing tasks.

We developed the Single-Leg Landing Error Scoring System (SL-LESS) to evaluate movement errors during a SLL based on the established LESS. Similar to the LESS, the SL-LESS instrument was developed around the construct that good landers will have fewer errors and better kinematics as compared to poor landers who have more errors and poorer kinematics during a SLL. The purpose of this study was to 1) determine inter- and intra-rater reliability of the SL-LESS, 2) and determine the content and construct validity of the SL-LESS when evaluating SLL. We hypothesized that the SL-LESS would have at least moderate intra- and inter-rater reliability, and that it would be able to discriminate between good-landers and poor-landers biomechanics.

**METHODS**

**Content Validity**
The research team consisted of two experts with greater than 15 years of experience in clinical and biomechanical movement evaluation and three biomechanics graduate students. We evaluated the LESS rubric and removed 3 items not applicable to a single-leg task (stance width-wide, stance width-narrow, symmetric initial foot contact). A new item “pelvic drop” was added because of the high potential for frontal plane pelvic movement during a single-leg task. Angle thresholds for each item were determined by a reviewing existing values related to injury biomechanics during single leg squat and landing tasks.\textsuperscript{20,28-30} If threshold values for certain items were not found in the literature they were determined from averages from the pilot data. Pilot testing also identified difficulty in measuring the hip flexion angle (thigh relative to trunk) at initial contact because all participants were in a very neutral hip position at that point. So “hip flexion at initial contact” and “hip flexion displacement” were removed. “Ankle plantar-flexion displacement” was removed after pilot testing because no participant showed an error on this item. The final SL-LESS rubric has 10 items with additional details of instructions and definitions. (Appendix A). Pilot testing indicated fair inter-rater reliability, and good test-re-test reliability.\textsuperscript{31,32}

**Participants**

A power analysis based on previous data indicated that at least 10 participants per each of 3 groups were necessary for adequate power.\textsuperscript{12} Thirty participants volunteered for the study, however total of 28 participants (age 24.79 ± 2.36 yrs, height 1.70 ± 0.07 m, weight 62.14 ± 9.64 kg, BMI 21.54 ± 3.48 kg/m\textsuperscript{2}) completed the study (2 lost due to follow-up). Inclusion criteria were being female, 18-30 years old, and participating in physical activity (at least 30 minutes/day, 3-4 days/ week). Participants were excluded if they had a history of surgery, injury within the previous six months, current pain in the back or lower extremities or were pregnant. Only females were enrolled in this study because of known poor landing biomechanics during SLL and a greater risk for injury than males.\textsuperscript{33} All participants provided written informed
consent and the study was approved by the university institutional review board.

**Procedures**

Two laboratory testing sessions were at least 48 hours apart. During the first session participants completed a questionnaire about injury history, current injury, and physical activity level. Height and weight were recorded, and standard neutral shoes (Saucony Jazz, Lexington, MA) were worn by each participant to minimize variability in shoe types.

The SLL task (Figure 1) was adapted from the DLL task used in previous studies. During pilot testing we determined that a 30cm tall box led to many landing failures and was too high for most participants to comfortably jump off and land on one leg. Similarly, the distance of the target being 50% of the height away was extremely difficult for many people to perform. Therefore, the box height was reduced to 20 cm and the target distance changed to 25% of height, resulting in pilot subjects being able to consistently and successfully perform the task.
Participants were introduced to the SLL with standardized verbal instructions while the task was demonstrated. “Stand on your preferred leg on top of the box, then jump out and land on the target on the same leg. Immediately after landing jump off that leg as high as you can. Your arms can move freely”. The participants’ preferred leg was identified by asking which leg felt more comfortable completing the SLL task with and data was then recorded from this leg. We chose to only test the preferred leg to give participants the choice of which leg they felt most comfortable performing the task on to minimize apprehension. Additional details about the SLL task instructions can be found in the Supplemental Material. A trial was unsuccessful if the participant did not jump off one foot, jumped vertically off the box, did not land with their entire foot on force plate, touched the ground with the non-supporting leg, lost balance/fell, or did not complete the task in a fluid motion. Five SLL trials were performed while only 2D data were recorded. However, the first and last trial were not analyzed to reduce variability in performance. The data from the middle 3 trials were averaged. During session two the same SLL procedure was repeated with both 2D and 3D data recorded.

Measurements
Two-dimensional data were collected using two video cameras (Canon VIXIA HF-R52, Sony Corp., San Diego, CA) on tripods placed 3.6 m anterior and 3.6 m lateral to the test limb at a height of 95 cm. Video recordings were captured at 60 Hz. For identification of anatomical landmarks on the 2D video, adhesive stickers were placed on the anterior superior iliac spine, greater trochanter, lateral femoral epicondyle, lateral malleolus, center of the patella, and tip of the shoe in line with the great toe.

The 3D motion data were collected using a ten-camera Eagle Digital Camera System (Recording at 200Hz) and Cortex software, version 5.5 (Motion Analysis Corp., Santa Rosa, CA). Kinetic data were collected at 1000 Hz, synchronously with the motion data, utilizing a Bertec force plate (Bertec Corp., FP4060-NC, Columbus, OH). The same researcher placed 32 individual and clustered reflective markers on the body to create a six degrees of freedom marker set using a standard protocol. 

Figure 2A. Anterior view of marker set placement for 3D standing calibration trial

Figure 2B. Posterolateral view of marker set placement for 3D standing calibration trial
Data Analysis: SL-LESS
Two raters who were not involved in the instrument development process, attended a training where they were given instructions about using the rubric. Both raters practiced the rating process and reviewed their results with the research team to reach consensus. Frontal and sagittal plane 2D videos were time-synchronized based on initial contact (frame when the shoe first contacted the ground), using video analysis software (Dartfish Connect, v8; Dartfish Inc., Fribourg, Switzerland). The point of maximal knee flexion which was defined as the deepest point of knee flexion. Raters independently viewed the videos in Dartfish and scored them using the SL-LESS rubric, and remained blinded to each other's scores.

Dichotomous ratings of “1”, indicating an error was present or “0” if the error was not present were used consistent with the original LESS. To accommodate for the potential increased variability of movement from trial to trial in the single-leg task, we chose to define an error on an item if the error was present in 2 or 3 out of 3 trials. No error was marked if an error was seen in 0 or only 1 out of 3 trials. The total score was the sum of all items with a maximum score of 10 points.

Consistent with the approach in the development of the original LESS (Padua, 2009) we created categories based on landing performance and total SL-LESS score. Padua et al had a very large data set and were able to create relatively even quartile categories based on total LESS score. Upon review of our data set, all the scores clustered between 1 and 6 out of the possible 10 points (Figure 3). Thus we decided to divide the group into thirds: total scores of ≤ 2 were categorized as “good landers”, total scores of 3 were “moderate landers” and total scores of 4 or greater were categorized as “poor landers”. To conserve power with the smaller sample size we chose to compare only the good and poor groups, thus the moderate group was not used for analysis. The grouping resulted in 12 in the good-landers and 7 in the poor-landers groups.

![Figure 3. Distribution of total SL-LESS scores in the sample. (The good and poor groups were used for the validation analysis with the moderate group eliminated)]](image-url)
Data Analysis: 3D

Tracked data were exported from Cortex and processed using Visual3D software (C-Motion Inc., Rockville, MD). Kinematic data were filtered using a 4th order, zero-lag, recursive Butterworth filter with a cutoff frequency of 12 Hz, and the kinetic data with a cutoff frequency of 50 Hz. Trunk, hip, knee, and ankle joint angles were calculated using a joint coordinate system approach. Joint centers and segment definitions and orientation were calculated using standard approaches. Ankle, knee and hip joint angles were relative angles of the adjacent segments. Trunk and pelvis angles were relative to the global axis. Angles that were most representative of poor movement quality were selected for analysis (See Table 1). Trunk flexion and lateral flexion, hip flexion and abduction, knee flexion and abduction, and ankle dorsiflexion angles were extracted at the point of initial contact (GRF ≥20 N). Trunk flexion, pelvic drop, hip flexion, hip adduction, knee flexion, and knee abduction angles were extracted at the point of maximum knee flexion during the landing. Three kinetic variables with known relationships to lower extremity injury were extracted. External knee abduction moment (KABDM normalized to body mass, Nm/kg) at the point of maximum knee flexion, KABDM at IC, and peak vGRF between good and poor landers. We selected joint angles that best represented each of the items on the SL-LESS (Table 2) and kinetic variables known to relate to injury risk. All statistical analyses were done using SPSS version 27 (SPSS Inc, Chicago, IL) and hand calculations for the PABAK were completed in Excel for Windows 10 (Microsoft, Redmond, WA). p <.05.

RESULTS

For intra-rater reliability (Average κ=0.30±0.21, PABAK=0.60±0.21, %agreement= 0.84±0.12), the average PABAK statistic for 8 of the 10 items was at or above the κ statistic. Intra-rater reliability was high for items 4 and 10, good for items 1, 2, 5, and 7, and moderate for items 6, 8, and 9. The average percent agreement across all items was 84%, with perfect agreement for item 10. Moderate intra-rater reliability for SL-LESS total score was found (ICC (3,1)= 0.556) (Figure 4).
For item inter-rater (Average $\kappa=0.21\pm0.21$, PABAK=0.60$\pm0.28$, %agreement=0.79$\pm0.13$) the average PABAK statistic for 6 of the 10 items was at or above the $\kappa$ statistic. Intrarater reliability was high for item 5, good for items 1 and 7, moderate for item 9, and fair for items 2, 3, 6, and 8. The average percent agreement across all items was 79%, with items 4 and 10 having perfect agreement. Good inter-rater reliability was found for SL-LESS total score with an (ICC $(2,1)= 0.663$) (Figure 5).

![Intrareliability by Item](image1)

**Figure 4.** Intrarater Reliability of SL-LESS rubric items. *prevalence adjusted, bias adjusted kappa (PABAK)*

![Interreliability by Item](image2)

**Figure 5.** Interrater Reliability of SL-LESS rubric items. *prevalence adjusted bias adjusted kappa (PABAK)***
Results of the construct validity analysis indicated the SL-LESS was able to identify significant differences in several biomechanical variables between poor and good landers. (Table 1) When compared to poor landers, good landers displayed significantly greater hip (F(1,19)=5.66, p=.029) and trunk flexion at IC (F(1,19)=.516, p=.036), and greater hip (F(1,19)=4.76, p=.043) and knee flexion at MKF (F(1,19)=4.73, p=.044). Good landers showed significantly lower peak vGRF (F(1,18)=9.32, p=.007) and lower KABDM at initial contact (F(1,18)=11.67, p=.003).

<table>
<thead>
<tr>
<th>Joint Angles- Initial Contact (degrees)</th>
<th>f values</th>
<th>P value</th>
<th>Good (n = 12)</th>
<th>Poor (n = 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle Dorsiflexion</td>
<td>1.93</td>
<td>0.18</td>
<td>-15.3 (12.1)</td>
<td>-22.0 (5.2)</td>
</tr>
<tr>
<td>Knee Flexion</td>
<td>1.89</td>
<td>0.18</td>
<td>-16.6 (6.8)</td>
<td>-12.6 (5.3)</td>
</tr>
<tr>
<td>Knee Abduction</td>
<td>2.49</td>
<td>0.13</td>
<td>1.8 (2.7)</td>
<td>-0.3 (3.2)</td>
</tr>
<tr>
<td>Hip Flexion</td>
<td>0.57</td>
<td>0.03*</td>
<td>42.1 (8.5)</td>
<td>33.1 (7.1)</td>
</tr>
<tr>
<td>Hip Abduction</td>
<td>4.09</td>
<td>0.06</td>
<td>-11.1 (3.1)</td>
<td>-7.6 (4.2)</td>
</tr>
<tr>
<td>Trunk Flexion</td>
<td>0.52</td>
<td>0.04*</td>
<td>17.9 (7.6)</td>
<td>10.7 (4.6)</td>
</tr>
<tr>
<td>Trunk Lateral Flexion</td>
<td>0.18</td>
<td>0.67</td>
<td>4.7 (7.6)</td>
<td>5.4 (5.8)</td>
</tr>
<tr>
<td>Knee ABD Moment External at IC (N*m/kg)</td>
<td>9.32</td>
<td>0.007*</td>
<td>-0.002 (.06)</td>
<td>-0.09 (.06)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Joint Angles- Maximal Knee Flexion (degrees)</th>
<th>f values</th>
<th>P value</th>
<th>Good (n = 12)</th>
<th>Poor (n = 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Flexion</td>
<td>0.47</td>
<td>0.04*</td>
<td>67.3 (6.9)</td>
<td>58.7 (10.4)</td>
</tr>
<tr>
<td>Knee Abduction</td>
<td>0.73</td>
<td>0.40</td>
<td>2.8 (5.4)</td>
<td>0.7 (4.7)</td>
</tr>
<tr>
<td>Hip Flexion</td>
<td>0.47</td>
<td>0.04*</td>
<td>54.6 (8.2)</td>
<td>42.4 (16.2)</td>
</tr>
<tr>
<td>Hip Abduction</td>
<td>2.09</td>
<td>0.16</td>
<td>1.0 (4.6)</td>
<td>4.4 (4.8)</td>
</tr>
<tr>
<td>Pelvic Drop</td>
<td>0.05</td>
<td>0.81</td>
<td>0.2 (2.7)</td>
<td>-0.0 (2.5)</td>
</tr>
<tr>
<td>Trunk Flexion</td>
<td>1.39</td>
<td>0.25</td>
<td>-159.6 (9.4)</td>
<td>-127.4 (95.4)</td>
</tr>
<tr>
<td>Trunk Lateral Flexion</td>
<td>0.14</td>
<td>0.71</td>
<td>3.9 (8.3)</td>
<td>4.6 (5.8)</td>
</tr>
<tr>
<td>Knee ABD Moment External at IC (N*m/kg)</td>
<td>0.93</td>
<td>0.093</td>
<td>-78 (.38)</td>
<td>-73 (.25)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ground Reaction Force</th>
<th>f values</th>
<th>P value</th>
<th>Good (n = 12)</th>
<th>Poor (n = 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak vGRF (N/kg)</td>
<td>11.67</td>
<td>0.003*</td>
<td>28.3 (4.8)</td>
<td>40.1 (10.1)</td>
</tr>
</tbody>
</table>

Table 1. Analysis of Variance Results from Construct Validity Analysis [* Significant a p < 0.05]

**DISCUSSION**

The purpose of this study was to determine the reliability and content and construct validity of the newly developed SL-LESS rubric to evaluate SLL landings. Our results indicate that one rater can evaluate an individual’s single leg landing across two different days with moderate reliability. Two raters can evaluate an individual’s movement at the same time point with good reliability. The SL-LESS is a valid way to discriminate poor landers who exhibit “stiff” landings with less hip and knee flexion and high vGRF from good landers who display more sagittal plane flexion and lower vGRF. The SL-LESS did not identify differences in frontal plane joint angles between poor landers and good landers, though the HADD angle measure was very close to significance and should continue to be explored. A rubric assessment for a SLL landing did not previously exist, and this initial version of the SL-LESS has sufficient reliability and validity that clinicians can begin to use it to evaluate the SLL.

Our results indicated moderate to good reliability for most of the items, and moderate reliability for the overall score. There are several steps in our process that led to these positive reliability results. First, we...
established content validity of the instrument through the pilot testing. Second, we developed specific instructions and provided practice sessions for raters to establish consistency of scoring. Given that this was a novel task for most people, there may have been some variability in their task performance between trials or testing days, which may influence reliability. Due to only moderate intra-rater reliability, we suggest that further development of the tool is necessary before a clinician uses it over time as an outcome measurement.

We analyzed the PABAK statistic in addition to the kappa to minimize the influence of rater bias. Post hoc item analyses indicated some items had high prevalence index, and none had a high bias index. In our study, items 4 and 10 both had a high prevalence rate index, which indicates a greater prevalence of raters marking “no error” or good movement. None of the items showed a high bias index. Future studies with a larger, more heterogeneous sample are needed to further explore the prevalence of errors in some of the SL-LESS items. The PABAK scores were higher than kappa for a majority of the items analyzed, and we conclude are a better representation of the reliability of the instrument. Future studies examining the reliability of rubric assessments should continue to report both the kappa and PABAK statistics.

We examined each item of the SL-LESS to gain information that will help in further developing the tool. The items with the lowest reliability also had specific joint angles measured in the item error descriptions. We developed the error descriptions based on evidence about cutoff angles or movements that indicated greater injury risk. An error in trunk flexion at IC was characterized by a trunk flexion angle of less than 15°. An error in knee flexion at IC characterized by a knee flexion angle of less than 15°. The Dartfish angular measurement tools were very sensitive to placement of the apex which then altered the angular measurement and could have resulted in more variability in the selection of error scores. Related to this, the items evaluating trunk (#6) and knee flexion (#8) displacement were then based on the measurements that were made from the angular positions at IC (#1 and 3), and also had lower reliability. A future recommendation for the SL-LESS is to make these error descriptions more general such as “The trunk is flexed less than approximately 15°”. This gives the rater some ability to look at an overall impression of the body position and determine if an error should be marked or not.

We began developing the SL-LESS around the construct that it would identify those with kinematics that are related to knee injury risk. Our construct validity results indicate that the SL-LESS is more valid to identify the “stiff landing” pattern of limited sagittal plane flexion and high vGRF than it is for identifying dynamic valgus. Though the HADD angle finding trended toward good landers being more abducted than the poor landers, it was not statistically significant likely because of the small sample size. Maloney et al (2018) found that participants were able to mitigate the higher ground reaction forces of single-leg landings by flexing more at the hips and knees to absorb the impact through greater center-of-mass displacement. Our results support this finding by showing that individuals who displayed greater sagittal plane flexion at the hips and knees had lower landing impact force. Although there was significant difference between groups for the KABD moment at initial contact, the difference was very small and the clinical meaningfulness is questionable. In general, our results indicate that the SL-LESS tool can be useful to screen for individuals who perform the SLL with a stiff landing and high impact force who may be at greater risk of injury during a single leg landing task.
The reliability and validity findings of our study are within the range of previous studies examining the SLL, although the type of movement and exact variables vary.\textsuperscript{30,48-50} Even with this variability, 2D analysis has shown moderate to good between- and within-session reliability and excellent inter-rater reliability,\textsuperscript{27} supporting the use of 2D analysis for single-leg landing tasks. It is difficult to compare and pool reliability of rubric assessments because of variability in how SLL have been performed in previous studies. Box heights have ranged from 18-40 cm and some protocols have used a drop jump and “stick” the landing while others use drop landing and then maximal vertical jump.\textsuperscript{18,20,50-53} This SLL protocol has been used in two previous studies, \textsuperscript{18,29} and we recommend this protocol be adopted in future research so that results can be more easily compared. In comparison to the original LESS for DLL had higher ICC values for interrater (0.84) and intrarater 0.91) reliability, however, this study had a sample of over 2,000 participants and a DLL is likely an easier task for participants to complete with less variability of movement.

This study has a few limitations. First, the sample size is relatively small and included only represented females and there are sex differences in drop landing biomechanics. Second, most participants were fair-skinned and not representing a wide variety of skin tones. Darker skin tones could influence the raters’ ability to see the stickers and anatomical landmarks and thus score the SL-LESS. Future research should include a more heterogenous sample with respect to gender and skin tones. We chose to use the stickers on anatomical landmarks to improve the visualization of the landmarks and thus the reliability. Future studies may consider adding a marker on the manubrium to be helpful in the lateral trunk lean measurement. However, we acknowledge that this makes the set-up process a bit longer per participant and may not be desirable in all settings. Finally, despite efforts to standardize a training and scoring protocol, the raters have the autonomy to subjectively score an item as they see fit. For cases that were in a gray area, some raters may have been more conservative and scored an error while others did not. Future research with a larger number of raters with varying experience should normalize the inherent variability of scoring.

The SL-LESS is the first rubric to evaluate movement during a SLL. Our results indicate a single rater can evaluate SLL movement across days with moderate reliability, and two raters can evaluate SLL movement on the same day with good reliability. The SL-LESS demonstrated construct validity in that it identified the “good landers” who displayed more flexion at the trunk, hips, and knees and lower landing impact force from the “poor landers” who landed with less trunk and hip, and knee flexion and higher impact landing force. Therefore, the SL-LESS tool is reliable and can be used to screen females performing the SLL to identify those with a stiff landing who may be at greater risk of injury. Clinicians can begin to use the SL-LESS protocol and evaluation tool to evaluate SLL landings for screening, performance, or clinical outcomes assessment. Future research should examine a larger more diverse population of athletes to confirm these findings.

REFERENCES


**Appendix A. Single-Leg Landing Error Scoring System Rubric and 3-D Angle Comparison for Construct Validity Analysis**

<table>
<thead>
<tr>
<th>SL-LESS Rubric Items and Definitions</th>
<th>Error (1)</th>
<th>No Error (0)</th>
<th>3-D angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Forward trunk flexion at initial contact (IC)</td>
<td>The angle between a line from the greater trochanter that bisects the trunk, and a vertical line is flexed &lt; 15º.</td>
<td>The angle between a line from the greater trochanter that bisects the trunk and a vertical line is flexed ≥15º.</td>
<td>Trunk flexion Hip flexion</td>
</tr>
<tr>
<td>2. Lateral trunk lean at IC</td>
<td>A vertical line from the center of the patella falls medial to the center of the manubrium.</td>
<td>A vertical line from the center of the patella falls on or lateral to the center of the manubrium.</td>
<td>Trunk lateral flexion</td>
</tr>
<tr>
<td>3. Knee flexion at IC</td>
<td>The knee is flexed &lt; 15º</td>
<td>The knee is flexed ≥15º</td>
<td>Knee flexion</td>
</tr>
<tr>
<td>4. Medial knee position at IC</td>
<td>A vertical line from the center of the patella is medial to the center of the ankle joint.</td>
<td>A vertical line from the center of the patella aligns with or is lateral to the center of the ankle joint.</td>
<td>Knee abduction Hip abduction</td>
</tr>
<tr>
<td>5. Ankle position at IC</td>
<td>The foot lands flat or heel to toe.</td>
<td>The foot lands toe to heel.</td>
<td>Ankle dorsiflexion</td>
</tr>
<tr>
<td>6. Forward trunk flexion displacement</td>
<td>Between IC and maximum knee flexion (MKF) trunk flexion remains the same.</td>
<td>Between IC and MKF additional trunk flexion occurs.</td>
<td>Trunk flexion Hip flexion</td>
</tr>
<tr>
<td>7. Pelvic drop</td>
<td>At MKF the contralateral pelvis drops below the level of the ipsilateral pelvis.</td>
<td>At MKF the contralateral remains level or is elevated compared to the ipsilateral pelvis.</td>
<td>Pelvic drop</td>
</tr>
<tr>
<td>8. Knee flexion displacement</td>
<td>The difference between knee flexion angle at IC and at MF is &lt; 45º.</td>
<td>The difference between knee flexion angle at IC and at MF is ≥ 45º.</td>
<td>Knee flexion</td>
</tr>
<tr>
<td>9. Medial knee displacement</td>
<td>At the point of maximum valgus, a vertical line from the center of the patella is medial to the center of the ankle joint.</td>
<td>At the point of maximum valgus, a vertical line from the center of the patella is lateral to or through the center of the ankle joint.</td>
<td>Knee abduction Hip abduction</td>
</tr>
<tr>
<td>10. Tibial Rotation (toe pointed in/out)</td>
<td>Between IC and MF, the foot is positioned in 30º or more of internal or external rotation.</td>
<td>Between IC and MF, the foot is positioned in less than 30º of internal or external rotation.</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Appendix B. Instructions for the Single-leg Landing Error Scoring System

SINGLE-LEG LANDING ERROR SCORING SYSTEM (SL-LESS)

SINGLE-LEG DROP VERTICAL JUMP (SLDVI) TASK INSTRUCTIONS

- Box height = 20cm
- Landing target distance = 25% of participants height
- Instructions
  - Stand on your preferred leg on top of the box, then jump out and land on the target on the same leg. Immediately after landing jump off that leg as high as you can. Your arms can move freely
- Practice trials
  - Stand on the floor on one leg and jump forward to the landing target 2-4 times.
  - Stand on the 20 cm box on one leg and jump forward to the landing target for 2-4 more trials.
  - Rest at least 30 seconds between jumps, with more if desired by the participant.

SCORING INSTRUCTIONS

- Use the first three valid trials. Valid trial criteria include all of the following:
  - Subject jumped off one foot.
  - Subject jumped forward, not vertically high into the air.
  - Entire foot landed on the force plate.
  - Maintained balance after second landing.
  - Opposite foot did not touch down until after second landing.
- Synchronize the frontal and sagittal plane videos to the frame of initial contact (first frame that the shoe contacts the ground).
- Create a new event at the point of initial contact
- Use the angle tool for scoring items #1, 3, 6 and 8.
  - For #1, and 6 Place the apex of the angle on the greater trochanter marker first, then make a 90° angle. Then align the horizontal arm with the midline of the trunk.
  - For #3 and 8 place the apex of the angle on the knee marker, then align the arms with the greater trochanter marker and the lateral malleolus marker.
  - Write down the degree amount on the score sheet for each of these items.
- Use the vertical line tool for scoring items #2, 4, and 9.
- Use the horizontal line tool for scoring item #7.
- If there is uncertainty to whether an item is an error or no error, mark it as an error.
- The Overall score is the sum of all the Final Item Scores.
Appendix C. SL-LESS Scoring Sheet

<table>
<thead>
<tr>
<th>Item and Error Descriptions</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Final Score</th>
</tr>
</thead>
</table>
| **1. Forward trunk flexion at initial contact (IC)** | ERROR (1) 
The angle between a line from the greater trochanter that bisects the trunk, and a vertical line is flexed <15°. | NO ERROR (0) 
The angle between a line from the greater trochanter that bisects the trunk, and a vertical line is flexed ≥15°. |
| **2. Lateral trunk lean at IC** | ERROR (1) 
A vertical line from the center of the patella falls medial to the center of the manubrium. | NO ERROR (0) 
A vertical line from the center of the patella falls on or lateral to the center of the manubrium. |
| **3. Knee flexion at IC** | ERROR (1) 
The knee is flexed < 15°. (measured ≥165°) | NO ERROR (0) 
The knee is flexed ≥15°. (measured ≤165°) |
| **4. Medial knee position at IC** | ERROR (1) 
A vertical line from the center of the patella is medial to the center of the ankle joint. | NO ERROR (0) 
A vertical line from the center of the patella aligns with or is lateral to the center of the ankle joint. |
| **5. Ankle position at IC** | ERROR (1) 
The foot lands flat or heel to toe. | NO ERROR (0) 
The foot lands toe to heel. |
| **6. Forward trunk flexion displacement** | ERROR (1) 
Between IC and maximum knee flexion (MKF), trunk flexion remains the same. | NO ERROR (0) 
Between IC and MKF, additional trunk flexion occurs. |
| **7. Pelvic drop** | ERROR (1) 
At MKF, the contralateral pelvis drops below the level of the ipsilateral pelvis. | NO ERROR (0) 
At MKF, the contralateral remains level or is elevated compared to the ipsilateral pelvis. |
| **8. Knee flexion displacement** | ERROR (1) 
The difference between knee flexion angle at IC and at MKF is < 45°. | NO ERROR (0) 
The difference between knee flexion angle at IC and at MKF is ≥ 45°. |
| **9. Medial knee displacement** | ERROR (1) 
At the point of maximum valgus, a vertical line from the center of the patella is medial to the center of the ankle joint. | NO ERROR (0) 
At the point of maximum valgus, a vertical line from the center of the patella aligns with or is lateral to the center of the ankle joint. |
| **10. Tibial rotation (toe in; toe out)** | ERROR (1) 
Between IC and MKF, the foot is positioned in 30° or more of internal or external rotation. | NO ERROR (0) 
Between IC and MF, the foot is positioned in less than 30° of internal or external rotation. |

**TOTAL OVERALL SCORE**
(Sum of Final Item Scores)