Neuromuscular Control of Vertical Jumps in Female Adolescents

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Background: Poor landing mechanics are considered deficits in neuromuscular control and risk factors for lower extremity injury. The Landing Error Scoring System (LESS) has been used to assess the neuromuscular control of landing mechanics for the first landing in a drop vertical jump (DVJ) task. However, the second DVJ landing may provide different results, warranting assessment.

Hypotheses: (1) LESS scores will differ between first and second DVJ landings across all female participants with (2) greater intraparticipant variability among the second landing compared with the first landing scores.

Study Design: Cross-sectional study.

Level of Evidence: Level 4.

Methods: A total of 13 gymnasts and 31 softball players (N = 44) performed 3 DVJ trials. The mean $\pm$ SD age of 44 female athletes was 16.46 ± 2.59 years. The LESS was scored using 2-dimensional video of each trial.

Results: There was a significant difference between the first and second DVJ landings ($P < 0.01$). All participants demonstrated higher LESS scores (worse landing mechanics) during the second DVJ landing (10.10 ± 2.25) than the first landing (6.97 ± 2.72).

Conclusion: The initial landing in a DVJ has been the focus of neuromuscular control studies using the LESS. This study found worse neuromuscular control during the second DVJ landing, which highlights the importance of evaluating landing mechanics beyond the initial landing.

Clinical Relevance: LESS analysis of both DVJ landings might improve neuromuscular control screening in female athletes and augment lower extremity and anterior cruciate ligament injury prevention programs.

Keywords: female athletes; landing biomechanics; lower extremity

Neuromuscular control plays a pivotal role in the incidence and recovery of lower extremity injuries, particularly at the knee, among athletes.^{14,16,29} Numerous neuromuscular screening tools have been developed to identify those at risk for injury by measuring an athlete's ability to simultaneously maintain anatomical alignment and dynamic control of the entire body during a specified activity.¹¹⁻¹³ Assessment of body alignment during landing activities is particularly important since many noncontact lower extremity injuries such as anterior cruciate ligament (ACL) injuries may occur with poor limb alignment during jumping, landing, or pivoting tasks.^{3,4,14,25,28,30} Among the many methods for documenting lower extremity neuromuscular control, the

evaluation of how well an athlete controls his or her body alignment when landing from a jump is popular.¹² The drop vertical jump (DVJ) activity (Figure 1) is a 2-part task that requires participants to drop from the edge of a 31-cm box to land on the ground below (first landing) before immediately jumping as high as possible and returning to the ground (second landing).^{8,12} Evaluation of the DVJ allows for analysis of a dynamic task that bears similarities to common sporting activities in which an athlete must prepare for a subsequent movement such as a vertical jump after an initial landing. During the second landing, the athlete is not focusing on performing a subsequent task, providing an opportunity to assess a less "planned" landing pattern. Interest in measuring landing during the DVJ has

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Figure 1. Motion sequence for drop vertical jump. Participants stood at the edge of 31-cm foam box, (a) dropped directly onto the ground below and then (b) immediately jumped as high as possible before landing on the ground for a second time. Data collected during motion elements at initial ground contact are indicated by a red asterisk.

focused on the first landing. However, the second landing may provide additional insight to an athlete's motor control.

Multiple studies have established that athletes exhibit less favorable biomechanics during unplanned motions compared with planned motions during tasks that are commonly associated with ACL injury such as a side-step maneuver.⁶ A recent 3-dimensional (3D) biomechanics study of female middle and high school basketball players also suggests that it is more difficult for participants to demonstrate ideal landing biomechanics and therefore control during the second landing of a DVJ task.¹ Unfavorable biomechanics, including smaller knee and hip flexion angles, were associated with the second landing ($P < 0.035$).¹ Biomechanics exhibited during a DVJ task that indicate neuromuscular control deficiencies are frequently evaluated in a clinical setting using a scaled assessment tool called the Landing Error Scoring System (LESS).²³ The 2-dimensional video analysis of athletes performing landing tasks such as the DVJ with LESS scoring, both in the clinic and on the sport fields, is gaining popularity.^{21,23} However, the utility of comparing biomechanics based on LESS scoring between the 2 different DVJ task landings is unknown. Comparison of LESS

scores between athletes of various sports is also not well established.

Many of the neuromuscular control assessments, including the DVJ task, have focused primarily on women participating in soccer and basketball, which are sports that have high knee injury incidence rates.^{10,17} Other women's sports that involve both repetitive landing tasks and report elevated ACL injury incidence rates have largely been excluded from development of screening tools. One such example is women's gymnastics, which has the second highest incidence of ACL tears per exposure at the collegiate level and the third highest rate of knee injuries at the high school level among all men's and women's sports studied.^{9,17,29} In addition, girls participating in fast pitch softball experience internal derangements of the knee and have significantly higher knee injury rates than boys in sex-comparable high school sports.^{19,29} High school softball players have a rate ratio of 3.06 (2.11-4.44) knee injuries per 10,000 athlete exposures.²⁹ Knee injuries also account for 8.7% of game injuries in collegiate women's softball, with 31% of these knee injuries involving the ACL.¹⁹ Female athletes participating in gymnastics and softball should be included in studies assessing lower extremity neuromuscular control and injury risk.

Biomechanical analysis of the DVJ offers potential study of 2 separate landing types: the drop from the box height as well as the landing after the vertical jump. However, the LESS originally only reported scoring the first DVJ drop landing of a forward distance of 50% height. This scored landing represents a movement pattern during which the person lands, then immediately transitions into a successive vertical jump movement.²¹ Increased LESS score variability might support the assertion that second landing is more difficult to control. As a result, clinicians may benefit from novel analyses of this second landing across athletic populations.

The purpose of this study was to investigate differences in DVJ first and second landings based on LESS score analysis among a cohort of female athletes who specialize in either gymnastics or softball. Our specific hypotheses were that (1) LESS scores differ significantly for the DVJ drop landing (first landing) and the vertical jump landing (second landing) across all female participants and (2) greater intraparticipant variability in the LESS score is expected for the second landing compared with the first landing.

METHODS

Forty-four female high school and collegiate athletes (mean age = 16.45 ± 2.59 years) were recruited from competitive training facilities within a 60-mile radius of the study facility. A total of 13 gymnasts and 31 softball players provided informed written consent for study participation following the guidelines of our institutional review board–approved study protocols (including assent from minors with parental approval and written consent). Female gymnasts and softball players aged 14 years and older participating in their sporting activity without injury for at least 3 months prior to enrollment were eligible for inclusion.

Table 1. Participant demographics by sport

	Age, y	Height, m	Weight, kg
Softball players	16.5 ± 2.4	1.68 ± 0.07	66.84 ± 13.52
College (n = 8)	19.9 ± 1.5	1.66 ± 0.07	72.50 ± 13.14
High school (n = 23)	15.4 ± 1.3	1.68 ± 0.07	64.87 ± 13.36
Gymnasts	16.3 ± 3.1	1.59 ± 0.09	55.09 ± 9.59
College (n = 3)	19.7 ± 2.1	1.55 ± 0.03	55.94 ± 1.31
High school (n = 10)	15.3 ± 2.6	1.60 ± 0.10	54.84 ± 11.04
Total	16.5 ± 2.6	1.65 ± 0.09	63.37 ± 13.51

Each athlete performed the DVJ task and were instructed to stand at the edge of 31-cm foam box, drop directly down onto the floor and then immediately jump as high as possible. The softball players wore their preferred noncleats training footwear and the gymnasts were tested barefoot and in their routine gymnastics training leotard. The DVJ activity was completed after the athlete returned to the ground for the second landing. This task was performed to allow 1 practice trial followed by data collection of 3 trials. Video recording in both the frontal and sagittal planes were collected for all trials. One reviewer assessed the video recordings of the DVJ trials for all participants to calculate the LESS scores. The 17 biomechanical measures were assessed for both the first and second landings following the established criteria described by Padua et al.²³ The first 11 categories of the 17 biomechanical measures examine the position of the lower limbs at the initial contact with the ground.²³ The last 6 measures examine the joint positions at the maximum displacement and the overall quality of the landing.

The LESS instructions guide the tester to assess 15 individual biomechanical measures and dichotomously award points if a specific movement error is absent (0) or present (1).²³ An ordinal scale of 0-2 is used to score measures of the task's overall impression and joint displacement. The total combined score of all 17 measures was calculated as the final LESS value.²³ Based on a previous study, the LESS score has good intrarater reliability, intraclass correlation coefficient ($ICC_{2,1}$) = 0.91, standard error of the mean (SEM) = 0.42.²³ The mean of the 3 LESS scores was used as the representative score for analyses of each athlete.

Data Analysis

To determine the intraparticipant variability of the LESS scores between the first and second landings the standard deviation for the 3 trials was calculated for each landing. The mean standard deviation for the first landing was then compared with the mean standard deviation of the second landing across the athletes. The LESS score is classified as ordinal data resulting in

implementation of nonparametric analyses for all LESS score comparisons. A Wilcoxon signed-rank test was performed for comparing the LESS values from first and second landings. Spearman's correlation coefficient analyses were performed to determine correlations of the LESS score to participant characteristics (age, height, and weight). For all statistical analyses, the significance was set at $P < 0.05$. The SPSS (version 24, IBM) statistical software was used for all statistical analyses.

RESULTS

In the sample of 44 females, the mean age for the 13 gymnasts was 16.3 years (SD = 3.1) and the mean age for the 31 softball players was 16.5 years (SD = 2.4). Participant demographics are described in Table 1. No relationship between LESS scores and participant demographics reached statistical significance for either landing; age (first landing: $r_s = 0.053$, $P = 0.734$; second landing: $r_s = 0.072$, $P = 0.643$), height (first landing: $r_s = -0.084$, $P = 0.588$; second landing: $r_s = -0.132$, $P = 0.394$), weight (first landing: $r_s = -0.184$, $P = 0.232$; second landing: $r_s = 0.094$, $P = 0.544$).

Comparison of LESS scores Between First and Second Landings

The mean LESS score differed significantly between the first (6.97 ± 2.72) and second (10.10 ± 2.25) landings of the DVJ, revealing that the mean second landing LESS score was greater (indicative of poorer neuromuscular control) than the first landing, across all 44 participants. This resulted in a 45% increase in the LESS score observed at the second landing, $Z = -5.031$, $P < 0.01$ (Figure 2).

Differences in LESS scores between each landing were also noted between sports. Among softball players, the LESS score for the second landing was significantly greater than that of the first landing, $Z = -4.371$, $P < 0.01$ (Table 2). Among the 13 gymnasts, the mean second landing LESS score was also significantly higher than the first landing, $Z = -2.622$, $P = 0.009$.

Intraparticipant variability of the LESS score across the 3 trials for each landing event demonstrates that the variation mean

Figure 2. Differences in average Landing Error Scoring System (LESS) scores between first and second drop vertical jump (DVJ) landings.

Table 2. Relationships of mean Landing Error Scoring System (LESS) scores by landing and sport

	LESS Value		
	First Landing	Second Landing	
Gymnasts, n = 13	8.23 ± 2.66	9.79 ± 2.04	Z = -2.622
			P = 0.009 ^a
Softball players, n = 31	6.44 ± 2.60	10.23 ± 2.35	Z = -4.371
			P < 0.01 ^a

^aReached established level of significance (P < 0.05).

between the 3 trials for the first landing (median = 1.00) was significantly less compared with the second across all participants, $Z = -2.107$, $P = 0.035$ (Figure 3). Among just the softball players, there was significantly lower variation in LESS scores (median = 0.58) at the first landing compared with the second (median = 1.53), $Z = -2.892$, $P = 0.004$. However, in gymnasts alone, there was no difference in variation between the 3 trials for the first landing (median = 1.0) compared with the second (median = 0.94), $Z = -1.434$, $P = 0.152$.

Comparison of the LESS Scores for Individual Sagittal Plane Items

The investigation to identify differences between LESS scores of sport-specific athletes led to comparison of the movement pattern in the sagittal plane. There were greater mean LESS scores for the independent items scoring sagittal biomechanics at the knee, hip, and trunk at time of initial contact (items numbered 1-4 on the LESS) for the second landing across all participants.² Among all female athletes, decreased hip

($Z = -3.331$, $P = 0.001$) and trunk flexion ($Z = -3.363$, $P = 0.001$) were observed in the sagittal plane at initial contact for the second landing compared with the first (Table 3). There was no difference in the LESS item for sagittal plane knee ($Z = -1.559$, $P = 0.119$) and ankle ($Z = -1.172$, $P = 0.241$) angles between the first and second landings. Among softball players alone, significantly decreased values for the hip flexion angle ($Z = -3.394$, $P = 0.001$) and trunk flexion angle ($Z = -3.229$, $P = 0.001$) were observed at the second landing. However, among the gymnasts, no significant differences were identified among any of the LESS items for the sagittal plane between the first and second landings (Table 3).

DISCUSSION

Study findings provide justification for use of the second landing for assessment of neuromuscular control and its relationship to injury risk. The LESS score is commonly used to provide a measurement of neuromuscular control using a classification

Figure 3. Variations in average Landing Error Scoring System (LESS) score between drop vertical jump landings.

Table 3. Mean scores for the 4 Landing Error Scoring System (LESS) sagittal plane joint angle items at initial contact by landing and sport

LESS Item	First Landing			Second Landing		
	All	Softball	Gymnastics	All	Softball	Gymnastics
Knee flexion angle	0.18 ± 0.31	0.15 ± 0.31	0.55 ± 1.03	0.31 ± 0.47	0.16 ± 0.29	0.51 ± 0.38
Hip flexion angle	0.42 ± 0.45	0.29 ± 0.40	0.59 ± 0.40	0.70 ± 0.38	0.68 ± 0.38	0.74 ± 0.39
Trunk flexion angle	0.45 ± 0.48	0.34 ± 0.45	0.69 ± 0.41	0.74 ± 0.39	0.70 ± 0.40	0.87 ± 0.29
Ankle plantar flexion angle	0.068 ± 0.21	0.063 ± 0.18	0.17 ± 0.35	0.045 ± 0.17	0.043 ± 0.19	0.026 ± 0.092

system of observed biomechanics during the initial landing of the DVJ task. The female gymnasts and softball players demonstrated a greater LESS score, indicative of poorer neuromuscular control, during the second DVJ landing compared with the first landing. This primary finding supports the first study hypothesis and is likely because of the apparent decreased knee, hip, and trunk flexion scored within the subcategories of the LESS score at the second landing. These biomechanical measures have been cited in the literature as poor landing mechanics that especially predispose individuals to injury.^{15,20,24,26} Such differences in landing kinematics also suggest variation in execution and physical demands between the 2 similar yet distinct landing types. While the initial landing purely results from a 31-cm drop, this first landing places physical and mental demands on the athlete since it requires

planning for the immediately subsequent vertical jump. The anticipation for the vertical jump forces the athlete to maneuver in a predetermined way to stay on task. The second landing concludes the activity and therefore does not require subsequent conscious mental or motor planning. This “unplanned” landing might be more representative of typical landings under various sporting conditions. Scoring both the first and second DVJ landings could offer assessment of an athlete’s neuromuscular control during 2 types of landings that occur in sporting activities: a landing that requires transitional planning for a subsequent movement and a landing without transitional planning.

Differences between first and second LESS scores within each sporting population are likely linked to differences in sport-specific training between gymnastics and softball.¹⁸ In this study,

softball players had a significantly greater degree of separation in the first and second landing scores. The gymnasts' LESS scores were more similar between the first and second landings with no significant difference in intraparticipant LESS variability between the landings. Gymnasts are taught to land with upright posture and decreased hip and knee flexion so that the lower extremities are straight and close together.⁷ Gymnasts' repetitive landing training likely explains the smaller degree of separation in their LESS scores between landings. Gymnasts are trained to land their tumbling routines in a consistent manner in order to avoid point deductions during competition and demonstrate different drop landing mechanics compared with recreational athletes without landing training.^{7,18} Despite the mandate of gymnastics judging criteria for this specific lower extremity positioning pattern during landing, decreased hip and knee flexion at impact is biomechanically unfavorable and increases ground reaction forces at landing.^{5,26} Gymnastics landing training might have facilitated greater consistency in landing biomechanics between the 2 DVJ landings. However, adherence to judging criteria may place gymnasts at risk for knee injury as indicated by slightly greater magnitude first landing LESS scores, which accounts for the error of landing with decreased hip flexion observed more frequently in the gymnasts.²⁶ Conversely, softball players rarely receive sport-specific landing training, which likely contributed to the greater separation in the first and second landing scores and significant difference in intraparticipant variability in LESS scores between the landings. Softball players exhibited more natural and "untrained" landing mechanics for the first drop landing such as greater knee flexion, which was reflected in their relatively lower magnitude first landing score. However, a lack of landing training could also be responsible for the softball players' poorer second landing mechanics and associated higher second landing LESS scores due to decreased control and increased frontal plane hip adduction angle exhibited during the second landing. Overall, further study of the influence of sport-specific training patterns on comparative landing biomechanics and injury risk is indicated for gymnasts and softball players.

The focused and preplanning state of the athlete during the first landing motivated the second hypothesis that there would be less variability between the 3 trials for the first landing compared with the second landing. This was reaffirmed by the greater degree of variation in LESS scores at the second landing compared with the first landing across all participants and among the softball players alone. The variability did not demonstrate significance among the gymnasts alone, likely because of the structured training provided to gymnasts for landing upright with minimal sagittal plane lower extremity joint flexion.

Because of the sample size being skewed with more softball players than gymnasts, this study did not compare LESS scores between sports. The landing biomechanics may differ between softball players and gymnasts. It is likely that the resultant ordinal scale used to create the composite LESS score reduces the sensitivity to distinguish between groups.

A previous study reported that LESS scores greater than 5 are associated with elevated ACL injury risk among elite-level youth

soccer players.²² Both the softball players and the gymnasts tested in the current study demonstrated mean LESS scores for both the first and the second landings that well exceeded the threshold of 5. While such scores demonstrate a breakdown in aligned lower extremity joint biomechanics, it is unknown if they are at risk for ACL injury. First, a 3-year longitudinal study of over 5000 high school and college athletes across sports reported that LESS scores did not predict ACL injury incidence.²⁷ These investigators have also voiced the concern that the composite nature of the LESS score that is based upon largely dichotomous scoring may not have the necessary sensitivity to detect risk for ACL injury. Second, the testing method used in both these previous studies allowed multiple practice jumps prior to the 3 jumps used for the assessment, though it is unknown if 3 practice trials influences performance more than 1 practice trial. The third point to consider is that the first drop landing of the task was set at a targeted distance of 50% of the participant height for these 2 studies. The influence of this forward jump distance compared with a standard straight drop landing is not known. The decision for the current study to use a drop test without instruction for a forward 50% height landing was primarily driven by the growing use of the standard drop landing set up in 3D laboratory biomechanical studies. The study design was also chosen based on the observed preference of clinicians to perform the quicker setup of a standard drop landing test. The injury risk classification from the previous studies report LESS scores from only the first landing in their analyses. The findings presented in this current study support exploring the use of different landings for inclusion in future injury prediction studies.

Limitations

This study has limitations, including the very small number of gymnasts, which raises questions of generalizability. Also, there were differences in footwear among participants. However, this item may only have had a minimal impact on observed LESS scores, as the paired comparisons of the first and second landings are intraparticipant comparisons.

CONCLUSION

Study findings demonstrate that the LESS is effective in detecting differences between the first and second landing biomechanics across samples of female gymnasts and softball players. Type of sport-specific landing training might influence LESS scores and associated landing biomechanics. It is plausible that assessing both landings during the DVJ task may provide a more comprehensive view of an athlete's neuromuscular control. It is unknown which landing is more reflective of an athlete's true risk for injury.

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