Association Between Automated Landing Error Scoring System Performance and Bone Stress Injury Risk in Military Trainees

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ABSTRACT

Context: Lower extremity bone stress injuries (BSI) place a significant burden on the health and readiness of the US Armed Forces.

Objective: To determine if pre-injury baseline performance on an expanded and automated 22-item version of the Landing Error Scoring System (LESS-22) is associated with the incidence of BSI in a military training population.

Design: Prospective cohort study.

Setting: US Military Academy at West Point

Participants: 2,235 (510 females, 22.8%) incoming cadets

Main outcome measures: Multivariable Poisson regression models were used to produce adjusted incidence rate ratios (IRR) to quantify the association between pre-injury LESS scores and BSI incidence rate during follow-up, adjusted for pertinent risk factors. Risk factors were included as covariates in the final model if the 95% confidence interval (95% CI) for the crude IRR did not contain 1.00.

Results: A total of 54 BSI occurred during the study period, resulting in an overall incidence rate of 0.07 BSI per 1,000 person-days (95% CI: 0.05, 0.09). The mean number of exposure days was 345.4 (SD 61.12, range 3-368). The final model was adjusted for sex and BMI and yielded an adjusted IRR for LESS-22 score of 1.06 (95% CI: 1.002, 1.13; p=0.04), indicating that each additional LESS error documented at
baseline was associated with a 6.0% increase in the incidence rate of BSI during the follow-up period. In addition, six individual LESS-22 items, including two newly added items, were significantly associated with BSI incidence.

**Conclusions:** This study provides evidence that performance on the expanded and automated version of the LESS is associated with BSI incidence in a military training population. These results suggest that the automated LESS-22 may be a scalable solution for screening military training populations for BSI risk.

**Key words:** bone stress injury, lower extremity, screening, Landing Error Scoring System (LESS)

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**Key points:**

- The LESS has recently been expanded and automated. The new version has demonstrated promising reliability and validity, but has not yet been assessed for association with incident injury.
- The results of this study demonstrate that performance on the expanded and automated version of the LESS is associated with the incidence rate of BSI in a military training population.
- Given the minimal time and training requirements needed to administer the automated LESS, it may be useful to continue its development for potential use as a screening tool.

**INTRODUCTION**
Bone stress injuries (BSI) are one of the most common and potentially serious overuse injuries impacting the lower extremity in military service members.¹ A recent study reported the incidence to be 19 in every 1,000 male and 80 in every 1,000 female recruits during basic training.² The potential sequelae and loss of training time experienced from a BSI are substantial.³ There is substantial evidence that neuromuscular control and biomechanics (i.e. movement quality) in the lower extremities play an important role in the development of BSI,⁴ and several kinematic and kinetic variables have been identified as risk factors for BSI.⁴-⁸ The Landing Error Scoring System (LESS), is a reliable⁹ and valid⁹-¹² assessment of movement quality that has been used to examine the risk of BSI in military service members.¹³ A recent study by Cameron et al.,¹³ assessed movement quality using a manually scored version of the original 17-item LESS (LESS-17 scoresheet available in supplemental content) and found total score and five individual LESS items (ankle plantarflexion angle at initial contact, asymmetrical initial foot contact, stance width, trunk flexion angle at initial contact, and overall impression) to be significantly associated with the incidence rate of BSI in a sample of 1,772 Military Academy cadets. However, conducting and scoring the LESS manually requires six to seven minutes per individual and must be accomplished using video recordings assessed after screening.⁹ The time and personnel requirements of utilizing the manually scored LESS prohibits its use on a scale useful for large organizations like military units.¹⁴

The LESS-22 represents an expanded version of the LESS that was developed in the time since the Cameron et al. study completed data collection.¹⁵ The LESS-22
features five additional test items: asymmetrical loading, asymmetrical heel-toe/toe-heel landing, excessive trunk flexion displacement, asymmetrical timing, and “wobble” in real time (LESS-22 scoresheet available in supplemental material) to enhance the ability of the test to detect aberrant movement patterns associated with increased risk of Anterior Cruciate Ligament (ACL) injury. Though these five items were added specifically to increase the clinical utility of the LESS for assessing ACL injury risk, four of the newly added items (asymmetrical timing, asymmetrical heel-toe/toe-heel landing, trunk flexion, and asymmetrical loading) are associated with increased vertical ground reaction forces (vGRF), a recognized risk factor for BSI. The fifth item, knee “wobble,” represents a form of dynamic knee valgus, which has also been shown to be associated with BSI. These newly added LESS items may increase the association between global performance on the LESS (i.e. total score) and BSI injury risk. Additionally, identifying any new LESS item that has a significant association with BSI risk independent of total score may help inform future injury risk mitigation efforts. However, to date, no study has examined the association between performance on the LESS-22 and incident injury of the ACL or any other structure.

In addition to its expansion, the scoring of the LESS-22 has also recently been automated, resulting in real-time scoring ability. The automated LESS-22 uses a depth camera (Microsoft® Kinect™) and markerless motion capture software system (Physimax™, Physimax Technologies Ltd, Tel Aviv, Israel) to capture full-body kinematics and processes these data using cloud-based technology and proprietary kinematic machine learning algorithms. These algorithms “extract, track, and
dynamically refine virtual markers on each athlete’s body” to assess dynamic motion.\textsuperscript{15} Studies have found this version of the LESS to be reliable compared to expert raters,\textsuperscript{15,17} with an ICC\textsubscript{2,1} value of 0.80 for total LESS score\textsuperscript{17} and a prevalence and bias adjusted kappa statistic (PABAK) of 0.71 ± 0.27 averaged across all LESS items.\textsuperscript{15} Additionally, a recently published study demonstrated moderate levels of concurrent validity compared to kinematic measurements assessed using a three-dimensional kinematic motion capture system.\textsuperscript{18} This study demonstrated a moderate overall agreement between the automated LESS-22 scoring system and three-dimensional motion capture system (ICC\textsubscript{2,1} =0.58), with excellent agreement for 8 kinematic variables, good for 7, moderate for 10, and poor for 7 kinematic variables examined.\textsuperscript{18}

An individual can be assessed and scored using the automated LESS in approximately three minutes.\textsuperscript{18} Additionally, the automated LESS unit is portable\textsuperscript{18} and can be operated by a non-clinician trained in less than 15 minutes.\textsuperscript{18} Thus, the potential time, cost, and health savings presented by this automated version of the LESS are substantial relative to the original, manually scored LESS. Because of its scalability and rapidity, the automated version of the LESS has great potential for use in military training environments, in which the screening of thousands of trainees may need to be accomplished in a single day. BSI are an important target for screening efforts because they are one of the most frequent serious injuries incurred in military training populations,\textsuperscript{1} and are experienced at a much greater rate than many other injuries, including ACL injuries.\textsuperscript{2,19} Cameron \textit{et al.}\textsuperscript{13} established the utility of the LESS in a military training population by demonstrating an association between performance on
the manually scored version of the LESS-17 and incident BSI. However, the manually scored version of the LESS takes too long to administer and score to be useful at scale. Additionally, all five of the new LESS items added to create the LESS-22 have a strong theoretical association with BSI, potentially improving the strength of association between performance on the LESS and subsequent BSI. Therefore, the purpose of this study was to examine the association between performance on the automated LESS-22 and prospective BSI incidence in a military training population with a secondary purpose of identifying individual LESS-22 items significantly associated with BSI incidence.

Methods

Participants

Participants were first year cadets at the United States Military Academy (USMA). All participants were enrolled in a large cohort study examining risk factors for lower extremity injury in the years 2015 and 2016. Cadets who elected to participate in the parent study signed an informed consent document approved by [removed for blind review]. Potential participants were included if they were part of the incoming classes entering the USMA in the summer of 2015 or 2016 and were free of any health conditions precluding the completion of at least three successful trials of the LESS jump-landing task. In order to attend USMA, cadets must meet Department of Defense Medical Evaluation Review Board accession standards. Any potential participant was excluded if they did not successfully complete three trials of the LESS jump-landing task.
or complete and sign the informed consent form. Participants with incomplete datasets were excluded from all analyses utilizing the variable or variables for which they were missing data (Figure 1).

**Explanatory variables**

Participants provided demographic and self-reported lower extremity injury history information through use of a standardized, multiple-choice questionnaire. Sex was reported as female or male. Participants were asked if they had experienced a stress fracture in the six months prior to their arrival at the USMA. This was coded as dichotomous (yes/no). Body Mass Index (BMI) was calculated as weight in kilograms divided by height in meters squared (kg/m\(^2\)) and was taken from height and weight data recorded as a part of each cadet’s standardized Army Physical Fitness Test (APFT) administered the same week as the automated LESS-22 assessment.

**Response variables**

**Lower extremity bone stress injuries (BSI)**

In this study, the lower extremity was operationally defined as the hip, knee, and ankle joints and the bones of the pelvis, thigh, lower leg, and foot. A BSI was defined as any stress reaction or stress fracture in the bones of the lower extremity, diagnosed by a medical provider (physician, nurse practitioner, physical therapist, physician’s assistant, certified athletic trainer), and entered into a participant’s electronic medical record (EMR). Traumatic and other types of fractures were excluded. Injury data were obtained using the Cadet Illness and Injury Tracking System (CIITS) and Armed Forces
Health Longitudinal Technology Application (AHLTA) EMR system. The CIITS system generates data for each cadet extracted from clinical encounters documented in the AHLTA EMR system. Using standardized methods and criteria the CIITS and AHLTA records for each participant were searched for encounters with an associated diagnosis of a stress reaction or stress fracture of the lower extremity that occurred during the study period. Because all USMA cadets receive care in a closed healthcare system that uses the AHLTA EMR system, it is highly likely that all lower extremity BSI that occurred during the study period were included in the dataset.

Exposure days

Each participant’s days at risk were calculated as the total number of calendar days a cadet was on restricted lower extremity activity status due to injury or illness subtracted from 368 days (the length of the first academic year at the USMA). For example, if a cadet missed a total of five days due to injury or illness, that cadet had a total of 363 days at risk.

Statistical analyses

Descriptive statistics were calculated for all variables. Crude injury incidence rates per 1,000 person-days (IR = number of incident injuries / number of person-days) and incidence rate ratios (IRR = exposed IR / unexposed IR) were calculated for automated LESS-22 score and each potential covariate: previous stress fracture (dichotomized to yes/no), BMI (continuous), and sex. We elected to utilize the IRR rather than the injury proportion ratio (IPR), because the IPR only considers individuals who incur an injury rather than the overall population and is therefore utilized to look for patterns within
individuals who experience an injury. Because the LESS is designed to be utilized as a first-line screening tool, the IRR is the superior choice. Additionally, the IRR was utilized in the Cameron et al. study, facilitating a comparison of results.

An initial multivariate Poisson regression model using the natural log of calendar days as an offset variable was used to compare the association between LESS score and BSI incidence. Risk factors were included in the final model as covariates if the 95% confidence interval for the crude IRR did not contain 1.00. Participants with missing data were excluded from all multivariable analyses utilizing the variable for which data was missing. Each Poisson model was assessed for distributional appropriateness using the Deviance chi-square test, with a p-value $\geq 0.05$ indicating a Poisson distribution.

RESULTS

A total of 2,235 participants (510 females, 22.8%) enrolled in the study. The proportion of participants from the 2015 entering cohort was 49.9% (n=1,116). Thirty-two (1.43%) participants reported experiencing a stress fracture in the 6 months prior to reporting to basic training. The mean BMI of females enrolled in the study was 22.94 and the mean BMI of males was 24.67. A total of 54 lower extremity BSI occurred in 42 cadets during the study period, resulting in an overall incidence rate of 0.07 BSI per 1,000 person-days (95% CI: 0.05, 0.09). Thirty-four BSI occurred in males, and 20 in females. The mean time to injury was 105.54 days (SD=109.23), with a median of 43 days. The mean number of exposure days was 345.4 (SD 61.12, range 3-368). The
mean LESS-22 score was 5.22 (SD 1.99, range 0-14). Complete demographic data and BSI location counts are presented in Table 1.

In univariable analyses, total LESS-22 score was found to be significantly associated with BSI incidence (IRR= 1.08, 95% CI: 1.02, 1.15, p=0.01). Sex and BMI had 95% confidence intervals for their respective crude IRR that did not contain 1.00 and thus were included in the final model along with LESS-22 score (Table 2). The final model yielded an adjusted IRR for LESS-22 score of 1.06 (95% CI: 1.002, 1.13; p=0.04), indicating that each additional LESS-22 item documented at baseline was associated with a 6.0% increase in the incidence rate of BSI during the follow-up period, adjusted for sex and BMI. Additionally, six individual LESS-22 items were found to be significantly associated with the incident rate of BSI in univariable and multivariable analyses (Table 3). These included trunk flexion at initial contact (IRR=1.45, 95% CI: 1.05, 2.01), ankle plantarflexion angle at initial contact (IRR=1.59, 95% CI: 0.97, 2.59), asymmetrical foot contact (IRR=2.43, 95% CI: 1.07, 5.55), excessive trunk flexion displacement (IRR=1.52, 95% CI: 1.06, 2.19), knee “wobble” (IRR=2.96, 95% CI: 1.30, 6.75) and overall impression (IRR=3.08, 95% CI: 1.30, 7.33).

DISCUSSION

To the best of our knowledge, this is the first study to examine the association of performance on the expanded LESS-22 with BSI incidence in a military training population, as well as the first to do so using an automated version of any iteration of
the LESS. Our results demonstrate an association between performance on the automated version of the LESS-22 and risk of subsequent BSI, with each additional LESS item present associated with an increase of 6.0% in the incidence rate of BSI, adjusted for sex and BMI.

Our findings are similar to those for the manually scored LESS-17 used by Cameron et al. That study reported a significant univariable association between manually-scored LESS-17 scores and the incidence rate of BSI in two earlier USMA cohorts (2013 and 2014). However, that study did not find an association between performance on the LESS-17 and incidence rate of BSI once the LESS-17 score was adjusted for sex and cohort. Two key differences between the studies that may account for this are the exclusion of individuals with a history of BSI from the earlier study and the recent expansion of the LESS to include five additional items utilized in this study. Of the six individual LESS-22 items associated with increased incident BSI in this study (Table 3), two (excessive trunk displacement and knee “wobble”) are new items recently added to create the LESS-22 version of the test. This indicates that the expanded LESS-22 may have enhanced ability to detect movement patterns associated with elevated risk of BSI compared to the original LESS-17.

The LESS-22 items demonstrating the strongest associations with incident BSI were knee “wobble”, defined as “one or both of subject’s knees appears to ‘wobble’ or demonstrate a quick varus/valgus motion” during jump-landing (IRR 2.96 [95% CI: 1.30, 6.75], p=0.01) and overall impression (IRR 3.08 [95% CI: 1.30, 7.33], p <0.01),
defined as poor “if the subject displays a stiff landing and at least some frontal or
transverse plane lower extremity motion or if there is a large frontal or transverse plane
lower extremity motion” and excellent if an individual “displays a soft landing and no
frontal or transverse plane motion.” This is notable because a plurality of the BSI
observed in the study occurred in the tibia (40.7%, n=22; Table 1). Tibial stress
fractures are hypothesized to be the result of cantilever bending stresses resulting from
large vGRFs. The magnitude of cantilever bending moments is elevated by the
presence of “medial collapse,” or dynamic knee valgus, during gait, which causes lateral
migration of the vGRF relative to the midline of the tibia, increasing the cantilever
bending moment experienced by the tibia. These findings, in combination with recent
reports regarding the validity of the automated LESS-22 support the criterion and
construct validity of the automated version of this test.

The results obtained for individual LESS items in this study differ somewhat from
those of the previous study using the manually scored LESS-17. A total of three LESS
items were found to be significantly associated with BSI in both studies: Plantarflexion
angle at initial contact, trunk flexion angle at initial contact, and asymmetrical foot
contact. The greatest adjusted IRR values in Cameron et al. were reported for ankle
plantarflexion angle at initial contact (IRR =2.33, 95% CI: 1.36, 3.97) and asymmetrical
timing (IRR 2.53, 95% CI 1.34, 4.74). Similar magnitudes for these variables were
observed in this study (Table 3), with even stronger associations observed for the items
knee “wobble” (IRR 2.96, 95% CI: 1.30, 6.75) and overall impression.
A closer examination of the six LESS-22 items associated with increased BSI incidence in this study reveals that three (trunk flexion angle at initial contact, ankle plantarflexion angle at initial contact, and excessive trunk flexion displacement) are unique to the sagittal plane, one (knee “wobble”) is unique to the frontal plane, and two are multiplanar items (asymmetrical foot contact and overall impression). In 2017 and 2021, Mauntel et al. reported that the Physimax™ system provides more reliable and valid measures of joint kinematic variables in the sagittal plane compared to those in the frontal and transverse planes. This indicates that some additional frontal and transverse plane LESS items may be associated with BSI incidence but were not detected by the Physimax™ system. However, we do not believe this to be likely because Cameron et al. found only one frontal or transverse plane item (wide stance width) to be associated with increased BSI incidence in their sample.

There are several major strengths of the automated LESS-22 for screening in military populations. These include the system’s low cost, portability, and minimal personnel training and involvement for testing and scoring. These strengths overcome the relative drawbacks of moderate validity and strength of association with injury, particularly when one considers that currently the majority of incoming military personnel receive little or no movement quality or injury risk screening at initial entry. The automated LESS-22 shows promise for continued development as a first-line screening tool to screen incoming military personnel en masse to identify individuals with movement patterns associated with increased risk of BSI. Identified individuals could then be sent to second-level, in-depth screening provided by a movement quality
specialist such as an athletic trainer or physical therapist, or a laboratory-based
movement analysis using a three-dimensional motion capture system, such as those
produced by Vicon™ or Qualisys™. This two-tiered strategy would help direct limited
injury risk reduction resources to those individuals at greatest risk for BSI. The
identification of movement patterns associated with increased risk of BSI, such as the
six LESS-22 items displayed in Table 3, can also greatly aid in the creation of
efficacious injury prevention programs, as movement quality has been demonstrated
to be a modifiable risk factor for lower extremity injury that can be used to inform the
creation of injury prevention programs based on neuromuscular retraining through
corrective exercises.

Utilization of the automated LESS-22 also holds two large advantages over the
traditional means of BSI risk assessment, gait analysis. First, performance on the LESS
is associated with additional lower extremity injury risk, most notably those of the
ACL. Second, performance on the LESS is associated with several of the
biomechanical variables used in gait analysis, including ground reaction forces, but
with fewer equipment, time, and space constraints. Furthermore, performance on the
LESS has been shown to improve in response to a movement quality intervention
consisting of corrective exercises. These features make it a more useful tool than
traditional gait analysis for screening large groups such as incoming military personnel.
Future research should seek to determine if performance on the automated LESS-22 is
associated with future risk of other lower extremity injuries, such as ACL and lateral
ankle sprains, and to determine if performance on the automated LESS-22, in
conjunction with other explanatory variables, is associated with BSI risk at the individual, in addition to the aggregate, level. Additionally, future research should seek to assess the prognostic accuracy of the automated LESS-22 with a goal of identifying thresholds for preemptive movement quality-enhancing interventions.

**Limitations & strengths**

This study has several limitations. Despite having a large number of participants, the number of incident BSI (n=54, 2.4% incidence proportion) was still relatively low. Additionally, missing data on 248 participants (11.1%), primarily due to missing LESS-22 scores, may have resulted in a systematic error in our analyses. However, this is unlikely, as missing LESS-22 data was primarily due to training schedule conflicts (i.e. an entire company of cadets missed LESS-22 assessment to stay on schedule to complete training requirements). Because incoming cadets are randomly assigned to companies, this is very unlikely to have influenced our results. A final limitation is the possibility that some incident BSI were not captured. However, we believe this is highly unlikely given that all cadets are provided with medical care in a local, closed medical system. This study also has several strengths. First, the inclusion of members of both sexes in our sample allowed for examining the association of LESS performance and BSI in individuals of both sexes. Second, the large sample size resulted in adequate power to accurately evaluate the performance of the automated LESS. Finally, the closed healthcare system in the study environment likely resulted in the inclusion of virtually all incident BSI during the study period.
This study provides evidence that performance on the expanded LESS-22 assessed using an automated markerless motion capture software system is associated with the incidence rate of lower extremity BSI in a military training population. Each additional LESS item present was associated with an increase of 6.0% in the incidence rate of BSI. Coupled with the low cost and time constraints associated with its use, these results support further investigation of the automated LESS-22 as a scalable solution for first-line screening for BSI risk in military training populations.

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| Year of entry | n   | %   |
|---------------|-----|-----|
| 2015          | 1116| 49.9%|
| 2016          | 1119| 50.1%|
| Total         | 2235| 100%|

| Sex          | n   | %   |
|--------------|-----|-----|
| Female       | 510 | 22.8%|
| Male         | 1725| 77.2%|
| Total        | 2235| 100%|

| BMI<sup>a</sup> | mean | SD  |
|-----------------|------|-----|
| Female          | 22.94| 2.25|
| Male            | 24.67| 3.14|
| Overall         | 24.28| 3.05|

| Previous stress fracture | n   | %    |
|--------------------------|-----|------|
| Yes                      | 32  | 1.43%|
| No                       | 2178| 97.45%|
| Missing<sup>b</sup>      | 25  | 1.12%|
| Overall                  | 2235| 100%|

| Bone stress injuries incurred | n   | %   |
|-------------------------------|-----|-----|
| 0                             | 2177| 97.4%|
| 1                             | 42  | 1.9% |
| 2                             | 12  | 0.5% |
| Missing<sup>b</sup>           | 4   | 0.2% |
| Total                         | 2235| 100.0%|

| Bone stress injury locations | n   | %     |
|------------------------------|-----|-------|
| Femur                        | 4   | 7.4%  |
| Fibula                       | 3   | 5.6%  |
| Foot (unspecified)           | 11  | 20.4% |
| Leg (unspecified)            | 3   | 5.6%  |
| Metatarsal                   | 10  | 18.5% |
| Navicular                    | 1   | 1.9%  |
| Tibia                        | 22  | 40.7% |
| Total                        | 54  | 100.0%|

<sup>a</sup> 223 participants were missing BMI data

<sup>b</sup> Participants with missing data excluded from analyses using the missing variable
|                          | Unadjusted Estimates |                        | Adjusted Estimates |                        |
|--------------------------|----------------------|------------------------|--------------------|------------------------|
|                          | rate ratio           | 95% confidence interval| p-value            | rate ratio           | 95% confidence interval| p-value            |
| LESS-22 score            | ---                  |                        |                    | ---                   |                        |                    |
| Sex                      |                      |                        |                    |                      |                        |                    |
| Female                   | 1.08                 | 1.02, 1.15             | p=0.01             | 1.06                 | 1.002, 1.13           | p=0.04             |
| Male                     | ---                  | ---                    | ---                | ---                   | ---                    | ---                |
| Previous stress fracture |                      |                        |                    |                      |                        |                    |
| Yes                      | 1.42                 | 0.60, 3.35             | p=0.43             | ---                   | ---                    | ---                |
| No                       | ---                  | ---                    | ---                | ---                   | ---                    | ---                |
| Body mass index (BMI)    |                      |                        |                    |                      |                        |                    |
| ---                      | 0.86                 | 0.82, 0.90             | p=0.01             | 0.91                 | 0.86, 0.95            | p=0.01             |

*Not included in final multivariate model*
| LESS-22 Item                              | Unadjusted IRR (95% CI) | p-value | Adjusted IRR (95% CI) | p-value |
|------------------------------------------|-------------------------|---------|-----------------------|---------|
| Trunk flexion angle at initial contact   | 1.41 (1.01, 1.96)       | 0.04    | 1.45 (1.05, 2.01)     | 0.02    |
| Ankle plantarflexion angle at initial contact | 1.83 (1.11, 3.02)       | 0.01    | 1.59 (0.97, 2.59)     | 0.048   |
| Asymmetrical foot contact                | 2.69 (1.15, 6.26)       | 0.02    | 2.43 (1.07, 5.55)     | 0.03    |
| Excessive trunk flexion displacement     | 1.79 (1.24, 2.58)       | 0.02    | 1.52 (1.06, 2.19)     | 0.02    |
| Knee "wobble"                            | 3.32 (1.43, 7.73)       | < 0.01  | 2.96 (1.30, 6.75)     | 0.01    |
| Overall impression (2 vs 0)              | 4.04 (1.68, 9.71)       | 0.01    | 3.08 (1.30, 7.35)     | < 0.01  |

* also significant in Cameron et al. 2014
* expansion item on the LESS-22
* adjusted for sex and BMI