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Automated Landing Error Scoring System Performance and the Risk of Bone Stress Injury in Military Trainees

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

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

Design: Prospective cohort study.

Setting: US Military Academy at West Point, NY.

Patients or Other Participants: A total of 2235 incoming cadets (510 females [22.8%]).

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

Results: A total of 54 BSIs occurred during the study period, resulting in an overall incidence rate of 0.07 BSI per 1000 person-days (95% CI = 0.05, 0.09). The mean number of exposure days was 345.4 ± 61.12 (range = 3–368 days). The final model was adjusted for sex and body mass index and yielded an adjusted IRR for a LESS-22 score of 1.06 (95% CI = 1.002, 1.13; $P = .04$), 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, 6 individual LESS-22 items, including 2 newly added items, were significantly associated with the BSI incidence.

Conclusions: We provided evidence that performance on the expanded and automated version of the LESS was associated with the BSI incidence in a military training population. The automated LESS-22 may be a scalable solution for screening military training populations for BSI risk.

Key Words: lower extremity, screening

Key Points

- The Landing Error Scoring System (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.
- Performance on the expanded and automated version of the LESS was associated with the incidence rate of bone stress injuries in a military training population.
- Given the minimal time and training requirements needed to administer the automated LESS, continuing its development for potential use as a screening tool may be beneficial.

Bone stress injuries (BSIs) are one of the most common and potentially serious overuse injuries that affect the lower extremity in military service members.[1] Researchers[2] reported incidences of 19 in every 1000 male and 80 in every 1000 female recruits during basic training. The potential sequelae and loss of training time experienced from a BSI are considerable.[3] With substantial evidence, investigators showed that neuromuscular control and biomechanics (ie, movement quality) in the lower extremities played 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 reliable[9] and valid[9–12] assessment of movement quality that has been used to examine the risk of BSIs in military service members.[13] Cameron et al[13] assessed movement quality using a manually scored version of the original 17-item LESS (LESS-17 scoresheet available in supplementary material at http://doi.org/10.4085/1062-6050-0263.21.S1) and found the total score and 5 individual LESS items

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(ankle plantar-flexion angle at initial contact, asymmetrical initial foot contact, stance width, trunk-flexion angle at initial contact, and overall impression) were significantly associated with the incidence rate of BSI in a sample of 1772 Military Academy cadets. However, conducting and scoring the LESS manually requires 6 to 7 minutes per individual and must be accomplished by evaluating video recordings after screening.[9] The time and personnel requirements for the manually scored LESS prohibit its use on the scale required for large organizations such as military units.[14]

The 22-item version of the LESS (LESS-22) represents an expanded version of the LESS that was developed since Cameron et al[13] completed their data collection.[15] The LESS-22 features 5 additional test items—asymmetrical loading, asymmetrical heel-toe or toe-heel landing, excessive trunk-flexion displacement, asymmetrical timing, and "wobble" in real time (LESS-22 scoresheet available in supplementary material)—to enhance the ability of the test to detect aberrant movement patterns associated with an increased risk of anterior cruciate ligament (ACL) injury.[15] Although these 5 items were added specifically to increase the clinical utility of the LESS for assessing the ACL injury risk, 4 of the newly added items (asymmetrical timing, asymmetrical heel-toe or toe-heel landing, trunk flexion, and asymmetrical loading) are associated with increased vertical ground reaction forces (vGRFs),[16] a recognized risk factor for BSI.[2] The fifth item, knee wobble, represents a form of dynamic knee valgus, which has also been associated with BSI.[4] These newly added LESS items may increase the association between global performance on the LESS (ie, total score) and BSI injury risk. Additionally, identification of any new LESS item that has a significant association with BSI risk independent of the total score may help inform future injury risk-mitigation efforts. However, to date, no researchers have examined the association between performance on the LESS-22 and incident injury of the ACL or any other structure.

In addition to being expanded, the scoring of the LESS-22 has also recently been automated,[15] resulting in real-time scoring ability. The automated LESS-22 uses a depth camera (Microsoft Kinect) and a markerless motion-capture software system (Physimax Technologies Ltd)[15] 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.[15] Researchers found the automated version of the LESS-22 was reliable versus expert raters,[15,17] with an intraclass correlation coefficient (2,1) value of 0.80 for the total LESS score[17] and a prevalence- and bias-adjusted κ statistic (PABAK) of 0.71 ± 0.27 averaged across all LESS items.[15] Furthermore, in a recently published study,[18] researchers demonstrated moderate levels of concurrent validity compared with kinematic measurements assessed using a 3-dimensional kinematic motion-capture system. Moderate overall agreement was observed between the automated LESS-22 scoring system and 3-dimensional motion-capture system (intraclass correlation coefficient [2,1] = 0.58): excellent agreement for 8 kinematic variables, good for 7, moderate for 10, and poor for 7.[18]

An individual's performance can be assessed and scored using the automated LESS in approximately 3 minutes.[18] Also, the automated LESS unit is portable[18] and can be operated by a nonclinician trained in less than 15 minutes.[18] Thus, the potential time, cost, and health savings offered 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, where thousands of trainees may need to be screened in a single day. Bone stress injuries are an important target for screening efforts because they are one of the most frequent serious injuries incurred in military training populations[1] and are experienced at a much greater rate than many other injuries, including ACL injuries.[2,19] Cameron et al[13] established the utility of the LESS in a military training population by showing an association between performance on the manually scored version of the LESS-17 and incident BSIs. However, the manually scored version of the LESS takes too long to administer and score to be useful at scale.[15] Moreover, all of the new LESS items added to create the LESS-22 have strong theoretical associations with BSIs, potentially improving the strength of association between LESS performance and subsequent BSIs. Therefore, the purpose of our 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 the incidence of BSI.

METHODS

Participants

Participants were first-year cadets at the US Military Academy (USMA). All participants were enrolled in a large cohort study of risk factors for lower extremity injury in 2015 and 2016. Cadets who elected to participate in the parent study signed an informed consent document approved by the Institutional Review Board of the University of North Carolina at Chapel Hill. Cadets 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 3 successful trials of the LESS jump-landing task.[9] To attend USMA, cadets must meet Department of Defense Medical Evaluation Review Board accession standards. Any potential participants who did not successfully perform 3 trials of the LESS jump-landing task or complete and sign the informed consent form were excluded. Participants with incomplete datasets were excluded from all analyses using the variable or variables for which data were missing (Figure).

Explanatory Variables

Participants provided demographic and self-reported lower extremity injury history information via a standardized, multiple-choice questionnaire. Sex was reported as *female* or *male*. Participants were asked if they had experienced a stress fracture in the 6 months before their

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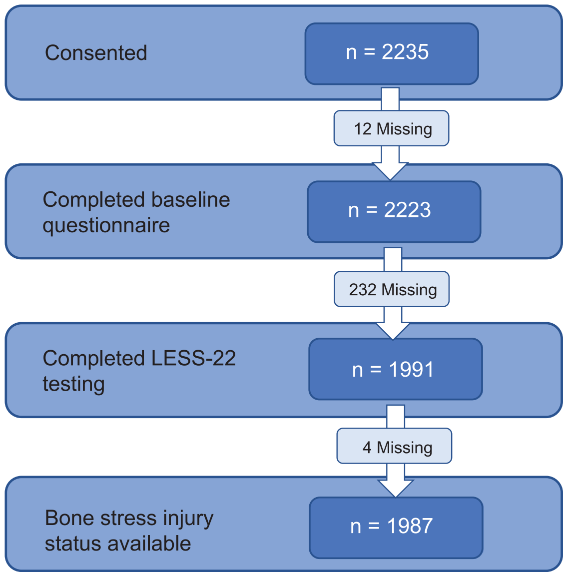

Figure. Flow diagram of participants enrolled in the study. Abbreviation: LESS-22, 22-item version of the Landing Error Scoring System.

arrival at the USMA; this variable was coded as dichotomous (*yes* or *no*). Body mass index (BMI) was calculated as weight in kilograms divided by height in meters squared (kg/m^2) from the height and weight data recorded during each cadet's standardized Army Physical Fitness Test, which was administered the same week as the automated LESS-22 assessment.

Response Variables

Lower Extremity BSIs. We operationally defined the *lower extremity* 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 assistant, or 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 from 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,[20,21] we searched the CIITS and AHLTA records for each participant for encounters with a 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 health care system that uses the AHLTA EMR system, it is highly likely that all lower extremity BSIs 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 5 days due to injury or illness, that cadet had a total of 363 days at risk.

Statistical Analyses

We computed descriptive statistics for all variables. Crude injury incidence rates (IRs) per 1000 person-days (IR = number of incident injuries/number of person-days) and incidence rate ratios (IRRs; exposed IR/unexposed IR) were calculated for the automated LESS-22 score and each potential covariate, namely, previous stress fracture (dichotomized to *yes* or *no*), BMI (continuous), and sex. We elected to use the IRR rather than the injury proportion ratio because the latter considers only those individuals who incur an injury rather than the overall population and is thus used to look for patterns within individuals who experience an injury.[22] Because the LESS is designed to be used as a first-line screening tool,[9] the IRR is the superior choice. Additionally, the IRR was used by Cameron et al,[13] which allowed us to compare our results with theirs.

An initial multivariate Poisson regression model using the natural log of calendar days as an offset variable was conducted to compare the association between LESS-22 score and BSI incidence. Risk factors were included in the final model as covariates if the 95% CI for the crude IRR did not contain 1.00. Participants with missing data were excluded from all multivariable analyses using the variable with missing data. Each Poisson model was assessed for distributional appropriateness using the Deviance chi-square test with a P value of $\geq$.05, indicating a Poisson distribution.

RESULTS

A total of 2235 participants (510 females [22.8%]) enrolled in the study. The proportion of participants from the 2015 entering cohort was 49.9% (n = 1116). Thirty-two (1.43%) participants reported experiencing a stress fracture in the 6 months before basic training. Mean BMI was 22.94 for females and 24.67 for males. A total of 54 lower extremity BSIs occurred in 42 cadets during the study period, resulting in an overall incidence rate of 0.07 BSI per 1000 person-days (95% CI = 0.05, 0.09). Thirty-four BSIs occurred in males and 20 in females. The mean time to injury was 105.54 ± 109.23 days, with a median of 43 days. The mean number of exposure days was 345.4 ± 61.12 (range = 3–368 days). The mean LESS-22 score was 5.22 ± 1.99 (range = 0–14). Complete demographic data and BSI location counts are presented in Table 1.

In univariable analyses, the total LESS-22 score was significantly associated with the BSI incidence (IRR = 1.08; 95% CI = 1.02, 1.15; P = .01). For their respective crude IRRs, the 95% CIs for sex and BMI did not contain 1.00 and thus were included in the final model along with the LESS-22 score (Table 2). The final model yielded an adjusted IRR for a LESS-22 score of 1.06 (95% CI = 1.002, 1.13; P = .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, 6 individual LESS-22 items were significantly associated with the incidence rate of BSI in univariable and multivariable analyses (Table 3). These items were trunk flexion at initial contact (IRR = 1.45; 95% CI = 1.05, 2.01), excessive trunk-flexion displacement (IRR = 1.52; 95% CI = 1.06, 2.19), ankle plantar-flexion angle at initial contact (IRR = 1.59; 95% CI = 0.97, 2.59), asymmetrical foot contact (IRR =

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Table 1. Demographic and Injury Information

Characteristic	No. (%) or Mean ± SD
Year of entry	
2015	1116 (49.9)
2016	1119 (50.1)
Total	2235 (100)
Sex	
Female	510 (22.8)
Male	1725 (77.2)
Total	2235 (100)
Previous stress fracture	
Yes	32 (1.43)
No	2178 (97.5)
Missing[a]	25 (1.12)
Overall	2235 (100)
Bone stress injuries incurred	
0	2177 (97.4)
1	42 (1.9)
2	12 (0.5)
Missing[a]	4 (0.2)
Total	2235 (100)
Bone stress injury location	
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)
Body mass index[b], kg/m_2	
Females	22.94 ± 2.25
Males	24.67 ± 3.14
Overall	24.28 ± 3.05

[a] Participants with missing data were excluded from analyses using the missing variable.
[b] Body mass index data were missing for 223 participants.

2.43; 95% CI = 1.07, 5.55), 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, we are the first researchers to examine the association of performance on the expanded LESS-22 with the 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 demonstrated an association between performance on the automated version of the LESS-22 and the 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.[13] Those investigators reported a significant univariable association between manually scored LESS-17 scores and the incidence rate of BSI in 2 earlier USMA cohorts (2013 and 2014). However, they did not find an association between performance on the LESS-17 and the incidence rate of BSIs once the LESS-17 score was adjusted for sex and cohort.[13] Two key differences between the Cameron et al[13] study and ours that may account for this discrepancy are the exclusion of individuals with a history of BSI from the earlier study and the recent expansion of the LESS to include 5 additional items[15] used in this study. Of the 6 individual LESS-22 items associated with increased incident BSIs in this study (Table 3), 2 (excessive trunk displacement and knee wobble) are new items recently added to create the LESS-22 version of the test.[15] This information indicates that the expanded LESS-22 may have an enhanced ability to detect movement patterns associated with an elevated risk of BSIs compared with the original LESS-17.

The LESS-22 items demonstrating the strongest associations with incident BSI were *knee wobble*, defined as "one or both of participant's knees appears to 'wobble' or demonstrate a quick varus/valgus motion"[23] during jump landing (IRR = 2.96; 95% CI = 1.30, 6.75; $P = .01$) and overall impression (IRR = 3.08; 95% CI = 1.30, 7.33; $P < .01$), 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."[9] This finding is notable because a plurality of the observed BSIs 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.[24] 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.[25] These results, in combination with recent reports regarding the validity of the automated LESS-22,[17,18]

Table 2. Crude and Adjusted Estimates for the LESS-22 Score and Covariates

Variable	Unadjusted Estimates: Rate Ratio	95% CI	P Value	Adjusted Estimates: Rate Ratio	95% CI	P Value
LESS-22 score	1.08	1.02, 1.15	.01	1.06	1.002, 1.13	.04
Sex						
Female	2.67	2.10, 3.39	<.01	2.07	1.57, 2.70	<.01
Male						
Previous stress fracture[a]						
Yes	1.42	0.60, 3.35	.43			
No						
Body mass index	0.86	0.82, 0.90	<.01	0.91	0.86, 0.95	<.01

Abbreviation: LESS-22, 22-item version of the Landing Error Scoring System.
[a] Not included in the final multivariate model.

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Table 3. **Significant Associations of LESS Items With Incident Bone Stress Injuries in Adjusted Analyses**

Variable LESS-22 Item	Unadjusted		Adjusted	
	IRR (95% CI)	*P* Value	IRR[a] (95% CI)	*P* Value
Trunk-flexion angle at initial contact[b]	1.41 (1.01, 1.96)	.04	1.45 (1.05, 2.01)	.02
Excessive trunk-flexion displacement[c]	1.79 (1.24, 2.58)	.02	1.52 (1.06, 2.19)	.02
Ankle plantar-flexion angle at initial contact[b]	1.83 (1.11, 3.02)	.01	1.59 (0.97, 2.59)	.048
Asymmetrical foot contact[b]	2.69 (1.15, 6.26)	.02	2.43 (1.07, 5.55)	.03
Knee wobble[c]	3.32 (1.43, 7.73)	<.01	2.96 (1.30, 6.75)	.01
Overall impression (2 versus 0)	4.04 (1.68, 9.71)	.01	3.08 (1.30, 7.33)	<.01

Abbreviations: LESS-22, 22-item version of the Landing Error Scoring System; IRR, incidence rate ratio.

[a] Adjusted for sex and body mass index.

[b] Also significant in the study by Cameron et al.[13]

[c] Expansion item on the LESS-22.

support the criterion and construct validity of the automated version of this test.

Our outcomes for individual LESS items differed somewhat from those in the previous study with manual scoring of the LESS-17. The following 3 LESS items were significantly associated with BSI in both studies: trunk-flexion angle at initial contact, plantar-flexion angle at initial contact, and asymmetrical foot contact. The greatest adjusted IRR values in Cameron et al[13] were reported for ankle plantar-flexion 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). We observed similar magnitudes for these variables (Table 3), with even stronger associations for knee wobble (IRR = 2.96; 95% CI = 1.30, 6.75) and overall impression (IRR = 3.08; 95% CI = 1.30, 7.33).

A closer examination of the 6 LESS-22 items associated with increased BSI incidence in our work revealed that 3 items (trunk-flexion angle at initial contact, excessive trunk-flexion displacement, and ankle plantar-flexion angle at intial contact) are unique to the sagittal plane, 1 (knee wobble) is unique to the frontal plane, and 2 are multiplanar items (asymmetrical foot contact and overall impression).[26] In 2017[15] and 2021,[18] Mauntel et al reported that the Physimax system provided more reliable and valid measures of joint kinematic variables in the sagittal plane than those in the frontal and transverse planes. This finding indicates that some additional frontal- and transverse-plane LESS items may be associated with the BSI incidence but were not detected by the Physimax system. However, we do not believe this is likely because Cameron et al[13] found only 1 frontal- or transverse-plane item (wide stance width) associated with increased BSI incidence in their sample.

The automated LESS-22 for screening in military populations has several major strengths, including the system's low cost, portability, and minimal personnel training and involvement required for testing and scoring.[18] These strengths overcome the relative drawbacks of moderate validity[18] and strength of association with injury, particularly when one considers that most incoming military personnel currently receive little or no movement-quality or injury-risk screening at entry.[14] The automated LESS-22 shows promise for continued development as a first-line screening tool[14,27] to assess incoming military personnel en masse and identify individuals who have movement patterns associated with an increased risk of BSI. These individuals could then undergo second-level, in-depth screening by a movement-quality specialist, such as an athletic trainer or physical therapist, or a laboratory-based movement analysis using a 3-dimensional motion-capture system, such as that produced by Vicon or Qualisys. This 2-tiered strategy would help direct the limited resources for injury-risk reduction to those individuals at greatest risk for BSI.[14] Identifying movement patterns associated with an increased risk of BSI, such as the 6 LESS-22 items displayed in Table 3, can also greatly aid in creating effective injury-prevention programs[28]; movement quality is a modifiable risk factor for lower extremity injury[29–31] that can be used to inform the creation of injury-prevention programs[28,32] based on neuromuscular retraining through corrective exercises.[29,33,34]

Use of the automated LESS-22 also holds 2 important advantages over the traditional means of BSI risk assessment, namely, gait analysis. First, poorer performance on the LESS was associated with additional lower extremity injury risk, most notably involving the ACL.[12,35] Second, performance on the LESS is associated with several of the biomechanical variables used in gait analysis,[1] including ground reaction forces,[9] but with fewer equipment, time, and space constraints. Furthermore, performance on the LESS improved in response to a movement-quality intervention consisting of corrective exercises.[29] These features make it a more useful tool than traditional gait analysis for screening large groups such as incoming military personnel. Researchers should determine if performance on the automated LESS-22 is associated with a future risk of other lower extremity injuries, such as ACL and lateral ankle sprains, and if performance on the automated LESS-22, in conjunction with other explanatory variables, is associated with the BSI risk at the individual, in addition to the aggregate, level. Additionally, investigators should assess the prognostic accuracy of the automated LESS-22 with a goal of identifying thresholds for preemptive interventions to enhance movement quality.

Limitations and Strengths

This study had several limitations. Despite including many participants, we showed that the number of incident BSIs (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 error was unlikely, as missing LESS-22 data were primarily due to training schedule conflicts (ie, an entire company of cadets missed the LESS-22 assessment in order to stay on schedule and complete training requirements). Incoming cadets are randomly assigned to

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companies, so this was not likely to have influenced our results. A final limitation was the possibility that some incident BSIs were not captured. Yet we believe this was highly improbable given that all cadets are provided with medical care in a local, closed medical system.

Our work also had several strengths. First, the inclusion of males and females in our sample allowed us to examine the association of LESS performance and BSIs in both sexes. Second, the large sample size resulted in adequate power for accurately evaluating the performance of the automated LESS. Finally, the closed health care system in the study environment likely resulted in the inclusion of virtually all incident BSIs during the study period.

CONCLUSIONS

We provided evidence that performance on the expanded LESS-22 assessed using an automated markerless motion-capture software system was associated with the incidence rate of lower extremity BSIs in a military training population. Each additional LESS item present was associated with an increase of 6.0% in the incidence rate of BSIs. Coupled with the low cost and time constraints associated with the LESS-22, these results support further investigation of the automated LESS-22 as a scalable solution for first-line screening of the BSI risk in military training populations.

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SUPPLEMENTAL MATERIAL

Supplemental Content. LESS-17 scoresheet.
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