Original Research

Medical and Biomechanical Risk Factors for Incident Bone Stress Injury in Collegiate Runners: Can Plantar Pressure Predict Injury?

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Investigation performed at Stanford University, Stanford, California, USA

Background: Bone stress injury (BSI) is a common reason for missed practices and competitions in elite track and field runners.

Hypothesis: It was hypothesized that, after accounting for medical risk factors, higher plantar loading during running, walking, and athletic movements would predict the risk of future BSI in elite collegiate runners.

Study Design: Cohort study; Level of evidence, 2.

Methods: A total of 39 elite collegiate runners (24 male, 15 female) were evaluated during the 2014-2015 academic year to determine the degree to which plantar pressure data and medical history (including Female and Male Athlete Triad risk factors) could predict subsequent BSI. Runners completed athletic movements while plantar pressures and contact areas in 7 key areas of the foot were recorded, and the measurements were reported overall and by specific foot area. Regression models were constructed to determine factors related to incident BSI.

Results: Twenty-one runners (12 male, 9 female) sustained $\geq$1 incident BSI during the study period. Four regression models incorporating both plantar pressure measurements and medical risk factors were able to predict the subsequent occurrence of (A) BSIs in female runners, (B) BSIs in male runners, (C) multiple BSIs in either male or female runners, and (D) foot BSIs in female runners. Model A used maximum mean pressure (MMP) under the first metatarsal during a jump takeoff and only misclassified 1 female with no BSI. Model B used increased impulses under the hindfoot and second through fifth distal metatarsals while walking, and under the lesser toes during a cutting task, correctly categorizing 83.3% of male runners. Model C used higher medial midfoot peak pressure during a shuttle run and triad cumulative risk scores and correctly categorized 93.3% of runners who did not incur multiple BSIs and 66.7% of those who did. Model D included lower hindfoot impulses in the shuttle run and higher first metatarsal MMP during treadmill walking to correctly predict the subsequent occurrence of a foot BSI for 75% of women and 100% without.

Conclusion: The models collectively suggested that higher plantar pressure may contribute to risk for BSI.

Keywords: biomechanics; gait mechanics; running; stress fracture; injury; pressure distribution; overuse injuries

Bone stress injury (BSI) is a common form of overuse injury characterized by accumulated microdamage, causing localized bone pain and limited physical activity and possibly progressing to fracture. This accumulation of microdamage may result from a combination of increases in repetitive loads, reduced time between periods of loading, anatomic factors, and biological insufficiencies that inhibit bone repair.[15,17,18] These injuries are common in the lower extremities of elite distance runners because of high training demands and loading characteristics, with 20% or more competitive runners developing a BSI annually.[2] This form of injury is particularly common in collegiate athletes.[10,14,16] Biological factors may influence risk for BSI, with low energy availability contributing to the risk for lower bone density and risk for injury as outlined in the Female Athlete Triad and Relative Energy Deficiency in Sport.[4,12] In particular, low energy availability, bone mineral density, and oligomenorrhea, amenorrhea, and age of menarche in women have been identified as risk factors for BSI and may have cumulative effects.[1,3,9,10,16] However, nearly 40% of all BSIs in collegiate athletes occur in the feet,

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so biomechanics at the plantar surface of the foot may also play an important role in this injury.[14]

Earlier studies associated foot anatomy features including arch height, forefoot, and hindfoot varus/valgus, and resting dorsiflexion with risk of metatarsal BSI.[5,6,20] These characteristics may increase stress to some bones of the foot during physiological loading.[6,20] Gait biomechanics can also affect BSI risk by influencing loading rates and joint moments.[21] These biomechanical factors have the common theme of affecting foot plantar pressure magnitude and distribution. Although other aspects, such as muscle activation, muscle insertion, ligament structure, and bone structure, influence bone loading and stress, foot plantar pressures may be associated with foot structure, gait, and loading. Thus, plantar pressure distributions may potentially be a useful tool to estimate the future risk of BSI and guide risk-reduction strategies in at-risk athletes such as runners.

Some studies have seen impressive predictive results using biological factors to predict the incidence of BSI in male and female runners,[1,10,16] while others have studied the possibility of using plantar pressure data for BSI prediction with less success.[5] While many studies show ties between the history of BSI and higher plantar pressure in specific regions of the foot, it is unclear whether this association is the cause or the symptom of the BSI.[11,19] High-risk populations such as elite distance runners are ideal candidates for study because the increased rate of injury in comparison with others allows for a smaller sample size and limits confounding variables such as general heath and history of disease.

The absence of follow-up data on incident BSIs after collection of plantar pressure measurements has limited our understanding of the value of these measurements for identifying those at risk for injury. The aim of this study was thus to measure the degree to which dynamic plantar pressure measurements could predict the future occurrence of BSIs in elite collegiate runners, after accounting for known biological risk factors. We hypothesized that (1) runners who exhibit higher plantar loading during running, walking, and athletic movements would be more likely to sustain a BSI; (2) higher plantar pressure can predict the subsequent occurrence of BSI independent of known biological risk factors; and (3) higher plantar pressure in the forefoot would be observed in those runners who sustain incident BSI in the feet.

METHODS

Study Design

After receiving institutional review board approval for the study protocol, we recruited 40 collegiate runners (16 female, 24 male) who participated in track and field at a single National Collegiate Athletic Association (NCAA) Division I program for this prospective observational study. The primary events of participants were middle-distance (800-m and 1500-m track races) or distance (5000-m and 10,000-m track races) track and field events. Eligible runners were actively on the team roster during the study enrollment period (2014-2015 academic year) and were not limited in ability to run because of an active injury. Written informed consent was given to and signed by each participant before participation.

Of the 40 athletes who agreed to participate in the study, 1 female participant was not included because of disqualification from participation in the collegiate track and field program, leaving 39 athletes enrolled. The CONSORT (Consolidated Standards of Reporting Trials) flow diagram shows the flow of participant enrollment (Figure 1).

At baseline, foot plantar pressure was measured during various tasks using a validated[13] insole pressure monitoring system (Pedar-X insole pressure monitoring system; Novel Electronics). This device monitors loads between the foot and the shoe by collecting plantar pressure distribution, which has been previously studied to characterize metatarsal injuries in athletes.[7,8] The development of any subsequent medically diagnosed BSIs was tracked during the remaining time of collegiate participation in the sport for each runner (up to 4 years).

Participants

Each participant completed a survey that characterized medical information and history such as height, weight, history of BSI, and biological risk factors, including history

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Ethical approval for this study was obtained from Stanford University (eprotocol No. 28420).

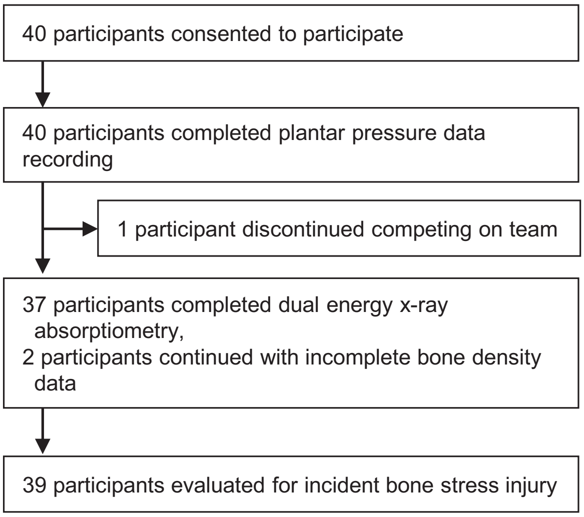

Figure 1. CONSORT (Consolidated Standards of Reporting Trials) diagram of study enrollment.

or current disordered eating and menstrual history in women (age of menarche and number of menstrual cycles each year). To account for effects of medications on menstrual function, the use of oral contraceptive pills and other hormones was also recorded. Based on the Female Athlete Triad and modified Female Athlete Triad risk assessments,[4,10] we calculated a triad cumulative risk score for each athlete, with a maximum possible score of 12 for women and 8 for men (higher score indicated more risk factors). Bone density was obtained at the lumbar spine and whole body using dual-energy x-ray absorptiometry (DXA) on GE Lunar iDXA (GE Healthcare). All scans were analyzed using enCORE Software Version 14.1 (GE Medical Systems Lunar). At the time of performing DXA, height and weight were measured to calculate body mass index.

Tasks and Plantar Pressure Measurements

During a single laboratory session, the left foot of each runner was fitted with a Pedar-X insole pressure monitoring system. Each runner was then asked to complete a set of athletic movements while plantar pressure data were collected at 99 Hz. Tasks included overground walking, treadmill walking at 3 mph (1.3 m/s), treadmill running at 6.5 mph (2.9 m/s), jump task, maximal effort shuttle run, and a cutting task. For each task, the following variables were extracted: peak pressure (kPa), maximum mean pressure (MMP; kPa), maximum force (N), contact area (cm^2), and impulse (Ns). Each of these variables was calculated for 7 different regions of the foot: hindfoot, lateral midfoot, medial midfoot, great toe, lesser toes, first metatarsal (MT1), and second through fifth metatarsals (MT2-5) (Figure 2). The manufacturer-supplied software was used for all data measurement and processing. This configuration parallels protocols using the Pedar-X system that were developed to study Jones fractures and dynamic loading in the foot.[7,8]

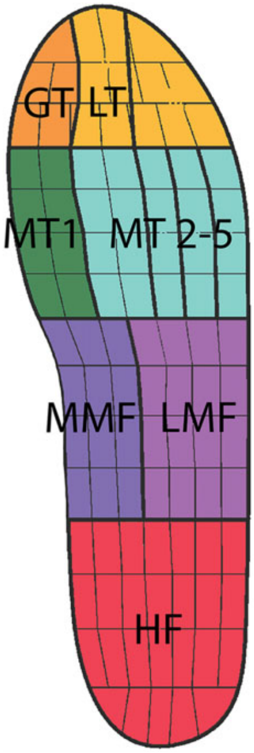

Figure 2. Pedar-X insole pressure sensors divided by plantar subsection. GT, great toe; HF, hindfoot; LMF, lateral midfoot; LT, lesser toes; MMF, medial midfoot; MT1, first metatarsal; MT2-5, second through fifth metatarsals.

Bone Stress Injury

Each participant was asked to record prior BSI, including date of diagnosis, anatomical location, and use of imaging to confirm injury. Medical records available during collegiate participation were also used to obtain information as all runners had the same team physician (M.F.) to determine medical clearance to participate during college. To be included, a BSI required physician diagnosis and radiographic confirmation and must have resulted from participation in the sport of running with occurrence before enrollment in the study.

Incident BSIs required the same criteria for inclusion in the study but were sustained after completion of plantar pressure measurements (diagnosed by a physician, confirmed by imaging, and resulting from participation in sport of running).

Statistical Analysis

To identify risk factors associated with incident BSI, we first compared the means of all variables between groups of no incident BSI versus $\geq$1 incident BSI. Men and women were considered separately. Those variables that were significantly different as measured by the Student t test or had an effect size (Cohen d) $>$0.3 were considered to be candidate variables for subsequent binary logistic regression. Next, binary logistic regression models were created with the candidate variables using a stepwise entry method. Because the history of BSI has been shown to be a strong predictor of future BSI, we opted to not include this factor in the models presented here. The rationale was that the strong effect of this variable makes it difficult to detect other potentially important factors related to sustaining a subsequent BSI. Alternate versions that include a history of BSI (as a binary variable) are shown in the Appendix. To avoid overfitting, models were created that included groups of related candidate variables (eg, biological risk factors or data from a single activity).

Four regression models incorporating both plantar pressure measurements and medical risk factors were created to predict the subsequent occurrence of BSI. The logistic regression models were evaluated based on their ability to correctly predict the observed BSI category for the cohort in female runners (model A) and male runners (model B). The overall model fit was evaluated based on a chi-square omnibus test, while the significance of individual coefficients was based on a Wald chi-square test. A similar approach was used to predict multiple incident BSIs regardless of sex (model C) and within the cohort who sustained incident BSIs isolated to the foot (model D). All statistical tests were run using SPSS Version 26 (IBM). $P \leq .05$ was considered significant.

RESULTS

Participant characteristics of the 39 included athletes (24 male, 15 female) are summarized in Table 1. All participants were NCAA eligible, meaning they were aged 18 to 23 years, and were observed for a period ranging from 1 season to 4 full years after baseline measurements, depending on their age at study enrollment. Table 2 summarizes the BSI history and outcomes for the study cohort, categorized by affected bones. Only 2 of the 15 participating female runners did not have a history of BSI.

TABLE 1
Characteristics of the Study Cohort ($N = 39$)[a]

	Men, n = 24	Women, n = 15
Height, cm	181.51 ± 7.92	171.02 ± 5.56
Mass, kg	69.70 ± 6.16	58.03 ± 5.10
Body mass index	21.2 ± 1.46	19.8 ± 0.95
History of BSI, n (%)	13 (54)	13 (87)
Triad cumulative risk score	0.83 ± 1.09	3.87 ± 2.30

[a] Data are reported as mean ± SD unless otherwise indicated. BSI, bone stress injury.

Model A: Predictors for Incident BSI in Female Runners

Regression model A was able to predict when $\geq$1 incident BSI occurred in female runners. The final model only included a single variable: MMP under the MT1 during jump takeoff ($R^2 = 0.554$; $P = .005$) (Tables 3 and 4). Although the coefficient for this variable was not deemed significant in the model ($P = .068$), the incident BSI group had significantly higher pressure ($P = .013$), and the model correctly predicted all incident BSI cases (n = 9) and 5 of 6 cases with no incident BSI (Table 3). The increase in MMP under the metatarsals for women with incident BSI was consistent throughout each task (Figure 3), with the jump takeoff task being the best predictor of BSI. As a measure of loading distribution during jump takeoff, we calculated the difference in MMP between MT1 and MT2-5. This difference was larger in female runners who sustained $\geq$1 incident BSI ($P = .055$) (Table 3). The Appendix contains regression coefficients and other model details for this and subsequent models.

Model B: Predictors for Incident BSI in Male Runners

Regression model B was able to predict $\geq$1 incident BSI in male runners. This model included impulse underneath the hindfoot and MT2-5 during walking, and impulse under MT2-5 during the cutting task ($R^2 = 0.748$; $P < .001$) and identified higher impulses in those with incident BSI (Table 3). However, only the coefficient for impulse under the hindfoot during walking was significant in this model ($P = .031$).

Model C: Predictors for Multiple Incident BSIs in Runners of Both Sexes

Model C was built to predict subsequent occurrence of multiple ($\geq$2) BSIs. In this model, men and women were combined into a single model to account for the relatively small

TABLE 2
Subsequent Occurrence (Incident) and History of BSI in the Study Cohort[a]

	History of BSI		Subsequent Incident BSI		History and Incident	
BSI Location[b]	Men, n = 13	Women, n = 13	Men, n = 12	Women, n = 9	Men, n = 11	Women, n = 9
Foot	1	3	0	4	0	2
Tibia	5	4	4	2	4	2
Fibula	1	0	0	0	0	0
Femur	5	1	4	3	4	1
Sacrum	5	8	5	7	4	7
Pars	1	0	1	0	1	0

[a] Data are reported as No. of participants. Ten men and 2 women did not have a bone stress injury (BSI) history or incident.

[b] As some participants sustained >1 BSI in >1 location, the total number of injuries in each column may exceed the total for that category.

TABLE 3
Characteristics and Variables Studied in Models A and B[a]

	Men		Women	
	No Incident BSI, n = 12	Incident BSI, n = 12	No Incident BSI, n = 6	Incident BSI, n = 9
Height, cm	180.54 ± 8.20	182.45 ± 7.87	171.02 ± 4.45	171.02 ± 6.48
Mass, kg	69.26 ± 5.62	70.17 ± 6.89	56.56 ± 4.31	59.01 ± 5.58
Body mass index	21.3 ± 1.2	21.1 ± 1.8	19.3 ± 0.7	20.2 ± 1.0
History of BSI, n (%)	2 (17)	11 (92)	4 (67)	9 (100)
Triad cumulative risk score	0.50 ± 0.80	1.17 ± 1.30	3.83 ± 1.47	3.89 ± 2.80
Model A results				
Jump takeoff MMP at MT1, kPa	19.17 ± 4.65	19.53 ± 4.94	15.56 ± 4.32[b]	22.71 ± 5.08[b]
Jump takeoff MMP at MT2-5, kPa	9.99 ± 2.40	9.81 ± 2.23	9.85 ± 0.85	11.48 ± 3.39
ΔMMP, MT1 to MT2-5, kPa	9.18 ± 5.05	9.72 ± 5.11	5.71 ± 4.29[b]	11.23 ± 5.34[b]
Model B results				
Walking impulse hindfoot, Ns	10.11 ± 3.49[b]	13.76 ± 2.97[b]	14.73 ± 3.65	13.98 ± 2.37
Walking impulse MT2-5, N.s	16.02 ± 2.32[b]	17.75 ± 1.35[b]	15.57 ± 1.58	17.00 ± 3.05
Cutting impulse, lesser toes, N.s	5.36 ± 2.06[b]	8.11 ± 3.33[b]	7.48 ± 2.88	6.53 ± 2.73
Model predictors, n (%)				
Model A correctly predicted			5 (83.3)	9 (100)
Model B correctly predicted	10 (83.3)	10 (83.3)		

[a] Data are reported as mean ± SD unless otherwise indicated. BSI, bone stress injury; MMP, maximum mean pressure; MT1, first metatarsal; MT2-5, second through fifth metatarsals.

[b] Within-sex significant difference between injury groups ($P \leq .05$).

TABLE 4
Demographic Variables for Multiple Incident BSIs in Men and Women[a]

	Men		Women	
	≤1 Incident, n = 22	Multiple Incidents, n = 2	≤1 Incident, n = 8	Multiple Incidents, n = 7
Height, cm	181.74 ± 8.26	179.07 ± 1.80	171.12 ± 5.08	170.92 ± 6.50
Mass, kg	69.85 ± 5.81	68.04 ± 12.84	58.01 ± 4.90	58.06 ± 5.72
Body mass index	21.2 ± 1.32	21.2 ± 3.54	19.8 ± 1.08	19.9 ± 0.85
History of BSI, n (%)	11 (50)	2 (100)	6 (75)	7 (100)
Model C results				
Triad cumulative risk score	0.64 ± 0.85	3.00 ± 1.41	3.13 ± 1.89	4.71 ± 2.56
Shuttle peak pressure at medial midfoot, kPa	13.32 ± 4.74	16.71 ± 3.27	13.77 ± 3.53	17.59 ± 4.77

[a] Data are reported as mean ± SD unless otherwise indicated. There were no significant differences between injury groups found when separated by sex. BSI, bone stress injury.

number of runners in each category, and sex was added as a potential predictor variable. The final model included 2 predictors: triad cumulative risk score and the peak pressure under the medial midfoot during the shuttle run ($R^2 = 0.574$; $P < .001$). The means of these variables were only significantly different between the injury groups when not separated by sex ($P \leq .023$) (Tables 4 and 5).

Model D: Predictors for Incident BSI Isolated to Foot in Female Runners

Finally, model D was created to predict the occurrence of foot BSI in women, since no male runners sustained a foot BSI during the study. The final model included the impulse of the hindfoot during the shuttle run and the MMP under the MT1 during treadmill walking ($R^2 = 0.786$; $P = .003$) (Table 6). Only 4 women developed a BSI in the foot during the study, 3 of which were in the metatarsals and 1 in the calcaneus. The model correctly predicted the occurrence of BSI in all but 1 runner with a metatarsal BSI. Remarkably, this model also correctly predicted 100% of female runners (n = 11) who did not sustain incident BSI of the feet. Only the impulse under the hindfoot during the shuttle run was significantly different between the comparison groups ($P = .032$). Neither of the coefficients was significant in the model, yet the forward Wald analysis procedure successfully entered each variable in the model, and the overall fit was significant.

DISCUSSION

The purpose of this study was to understand the predictive value of dynamic plantar pressure in runners for

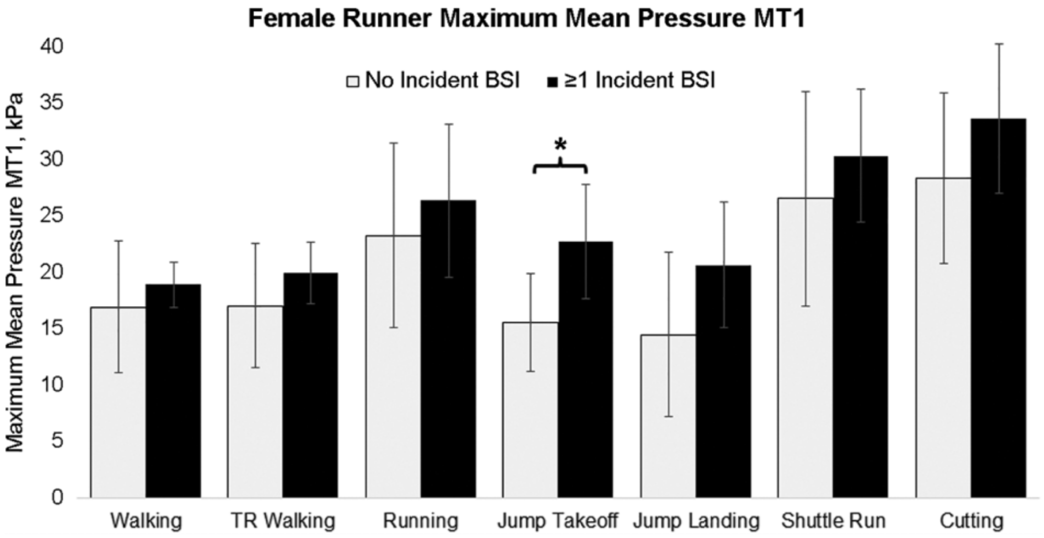

Figure 3. Comparison of maximum mean pressure under first metatarsal (MT1) of female runners during each task prescribed. Female runners with ≥1 incident bone stress injury (BSI) averaged higher maximum mean pressure under MT1. Error bars indicate SDs. *Significant difference between female injury groups ($P \leq .05$). TR, treadmill controlled.

TABLE 5
Variables Studied in Model C (All Runners, Predicting Multiple Incident BSI)[a]

	≤1 Incident, n = 30: 22 M, 8 W	Multiple Incidents, n = 9: 2 M, 7 W
Triad cumulative risk score	1.30 ± 1.62[b]	4.33 ± 2.40[b]
Shuttle peak pressure at medial midfoot, kPa	13.44 ± 4.40[b]	17.39 ± 4.31[b]
Model C correctly predicted, n (%)	28 (93.3); 22 M, 6 W	6 (66.7); 1 M, 5 W

[a] Data are reported as mean ± SD unless otherwise indicated. BSI, bone stress injury; M, men; W, women.
[b] Significant difference between injury groups ($P \leq .05$).

TABLE 6
Characteristics and Variables Studied in Regression Model D (Female Runners, Predicting Incident Foot BSI)[a]

		Women	
	Men, No Incident, n = 24	No Incident, n = 11	Incident, n = 4
Height, cm	181.51 ± 7.92	172.26 ± 4.65	167.64 ± 7.19
Mass, kg	69.72 ± 6.19	58.47 ± 4.22	56.84 ± 7.67
Body mass index	21.2 ± 1.5	19.7 ± 0.9	20.1 ± 1.0
History of BSI, n (%)	13 (54)	9 (82)	4 (100)
Triad cumulative risk score	0.83 ± 1.09	3.18 ± 1.72	5.75 ± 2.87
Shuttle impulse at hindfoot, N.s	3.36 ± 1.66	3.98 ± 1.49[b]	1.99 ± 1.18[b]
TR walking MMP at MT1, kPa	14.24 ± 3.04	18.03 ± 4.26	21.02 ± 3.24
Model D correctly predicted, n (%)		11 (100)	3 (75)

[a] Values are reported as mean ± SD unless otherwise indicated; BSI, bone stress injury; MMP, maximum mean pressure; MT1, first metatarsal; TR, treadmill controlled.
[b] Within-sex significant mean difference between injury groups ($P \leq .05$).

sustaining an incident BSI. We found that plantar pressure was able to predict incident BSI in male and female runners. Runners who developed BSI generally had higher peak pressures or impulses during walking, jumping, cutting, or shuttle tasks. This suggests that a combination of everyday and performance-related loading may contribute to BSI. Models A and B specifically support our first 2 hypotheses that higher plantar loading would be seen in those who would sustain BSIs, and higher plantar pressure measures would be predictive of sustaining future BSIs. Model D provides evidence to support our third hypothesis that higher forefoot loading would be indicative of incident

BSIs in the feet; notably, 4 women were in the injury group used to generate this model. Differences in variables between models accounting for sex, anatomic location, and number of BSIs sustained reflect the challenges in using plantar pressure measurements in clinical practice.

Predicting Incident BSI in Female Runners

Incident BSI in women could be predicted based on increased pressure under the MT1 during jump takeoff. The cause of higher plantar pressure localized to the MT1 cannot be determined by this study design; explanations may include forefoot valgus (pronation) but could also be associated with increased power and a shift toward forefoot loading. Notably, model A suggests that higher forces measured in the foot may predict increased risk of BSI at any anatomic location, including both the foot and general lower extremity.

Predicting Incident BSI in Male Runners

Incident BSI in male runners was predicted (model B) by higher impulses underneath the hindfoot and MT2-5 during walking as well as higher impulses under the lesser toes during the cutting task. Further analysis showed that the maximum forces in these conditions did not significantly differ between injury groups, so higher impulses can be more attributed to longer time under load. Additionally, no significant differences in height or weight were found between the groups; therefore, the simplest explanation for the higher times under load is increased chosen stride length in walking and decelerating to change direction. This difference may not be seen in the other running tasks because of differences in mechanics specific to the completion of each task. Therefore, this may not be a critical variable to use when predicting the subsequent occurrence of $\geq$1 BSIs in elite male runners.

Predicting Multiple BSIs in Male and Female Runners

A higher value on the triad cumulative risk score became a significant predictor for identifying those who sustained multiple incident BSIs (model C). Notably, model C was the only model combining the sexes, and no difference was found between the predicting power of the risk score when treating it as a continuous versus categorical variable. An increased triad cumulative risk score combined with higher peak pressure under the medial midfoot during the shuttle run could predict the majority of runners who would sustain multiple incident BSIs. Higher peak pressure in the medial midfoot may suggest lower or more compliant foot arches and/or a difference in mechanics when decelerating and shifting directions. Our findings are consistent with other studies in athletes and runners that have identified triad characteristics as strong biological risk factors for BSI.[1,9,10,16] The observation of multiple incident BSIs in those with combined triad risk factors and biomechanical risk factors is important to highlight in the management of runners. Our findings also support strategies for future injury prevention that include goals to alter plantar pressures in instances of high acceleration, such as jumping or changing direction, which may include foot strength physical therapy or retraining footstrike mechanics.

Predicting BSI in the Feet of Female Runners

We expected that plantar pressure would be a good predictor of BSI in the feet because of the close physical proximity of the measurement and injury sites. We found that lower hindfoot impulse during the shuttle run, plus higher MMP of the MT1 during walking, predicted incident BSI (model D). Less impulse under the hindfoot indicates a greater momentum change by the forefoot during acceleration/deceleration and possibly a shorter stride length.

Limitations

This study had several limitations. To account for the influence of speed on measured plantar pressure variables, walking and running tasks took place at fixed speeds on a treadmill and may not have been representative of the athletes' typical training efforts. Notably, the jumping and shuttle run tasks, which were performed overground and without the ability to control the effort of participants, had better predictive ability in the models and may reflect real-world changes in direction encountered in running. With the goal to capture a typical running pattern, we did not standardize footwear and allowed each participant to wear their own typical training shoes for data collection. Thus, the degree to which footwear affected plantar pressure distributions cannot be determined from the present data. Measures of foot alignment, footstrike, and cadence were not characterized and cannot be accounted for in our models for predicting injury.

Our statistical models did not include BSI history as a candidate variable. However, we present alternate versions in the Appendix. We note that including BSI history only slightly improved model B and that prior BSI is already included in the triad cumulative risk score. Additionally, some variables that had success in the models for predicting BSI were high acceleration and less controlled, such as jumping; this may explain why dynamic loading recorded at a standard laboratory speed would be challenging to characterize as a potential risk factor for BSI.

Despite these limitations, the study had several strengths, including a long prospective follow-up period (up to 4 years) and characterization of both biomechanical and clinically relevant medical risk factors for BSI. Our data add to a very limited body of work evaluating the ability for plantar pressure measurements to detect runners at increased risk for BSI.

CONCLUSION

We evaluated the degree to which higher plantar pressure measurements, combined with biological risk factors of the

Female Athlete Triad, could predict incident BSI in collegiate runners. We developed several models that were able to predict incident BSI in runners. The models collectively suggest that certain features of footstrike biomechanics such as increased forefoot valgus, a shift toward forefoot loading in general, and higher regional foot forces may contribute to risk for BSI. We recommend that future research using plantar pressure include tasks with self-selected speeds, faster running pace efforts, fatigue, and other methods to identify measures not studied here, such as horizontal ground-reaction forces.

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APPENDIX

Below are alternative models generated with history of BSI, triad cumulative risk, and body mass index (BMI) included as candidate variables within the group of medical demographic metrics.

Model A

Variables in regression function for alternative model A (female runners, predicting incident, BSI) are shown in Table A1. The overall model fit was $R^2 = 0.554$ ($P = .005$). Triad cumulative risk, history of BSI, and BMI were not chosen as predictor variables in the forward stepwise method ($P = .962$, .063, and .072, respectively).

TABLE A1[a]

Variable	β	Coefficient *P*
Jump takeoff MMP at MT1, kPa	0.451	.068
Constant	–7.972	.076

[a] MMP, maximum mean pressure; MT1, first metatarsal.

Model B

Variables in regression function for alternative model B while also including medical demographics are shown in Table A2. The overall model fit was $R^2 = 0.798$, $P < .001$. This model correctly predicted incident BSI in 10 of 12 and lack thereof for 11 of 12 male runners. Triad cumulative risk and BMI were not chosen as predictor variables in the forward stepwise method ($P = .679$ and 0.455, respectively).

TABLE A2[a]

Variable	β	Coefficient *P*
History of BSI	6.174	.038
Walking impulse at hindfoot, N· s	0.753	.102
Constant	–12.656	.073

[a] BSI, bone stress injury.

Model C

Variables in regression function for alternative model C (all runners, predicting multiple incident BSI) are shown in Table A3. The overall model fit was $R^2 = 0.574$, $P < .001$. Sex, history of BSI, and BMI were not chosen as predictor variables in the forward stepwise method ($P = .781$, .174, and .334, respectively).

TABLE A3

Variable	β	Coefficient *P*
Triad cumulative risk, total points	0.841	.009
Shuttle peak pressure at medial midfoot, kPa	0.285	.058
Constant	–8.138	.010

Model D

Variables in regression function for alternative model D while also including medical demographics are shown in Table A4. The final model only included triad cumulative risk, and it correctly predicted incident foot BSI in 3 of 4 female runners, with 1 false-positive result ($R^2 = 0.354$, $P = .041$).

TABLE A4

Variable	β	Coefficient *P*
Triad cumulative risk, total points	0.681	.138
Constant	–3.892	.063